ENVIRONMENTAL CONSIDERATIONS RELATING TO OPERATION AND MAINTENANCE OF THE TEXAS GULF INTRACOASTAL WATERWAY

by

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ABSTRACT

This study aims to identify potentially adverse environmental factors other than dredging associated with the operation and maintenance of the Texas Gulf Intracoastal Waterway. Field sampling was conducted along the waterway in January, May, and August 1975 to ascertain background water and sediment quality. To study the flow between Galveston Bay and Sabine Lake, a numerical model study was conducted of this reach of the waterway. Satellite imagery was used in the Lower Laguna Madre to study the circulation patterns and sedimentation rates. The following conclusions and recommendations were developed.

Conclusions:

1. The Intracoastal Waterway can transport water, pollutants, aquatic plants and animals from one river system to another.
2. The waterway and normal operational activities in the waterway did not appear to be a major source of pollutants but elevated concentration of nutrients and metals were usually associated with freshwater inflow.
3. In shallow, open-bay reaches of the waterway, the current patterns adjacent to the channel can have a significant effect on the shoaling rate.
4. The Intracoastal Waterway and associated dredged material islands have the potential of modifying circulation patterns and salinity levels in the bays and estuaries.

Recommendations:

1. A feasibility study should be conducted for constructing a control facility in the reach between Sabine Lake and Galveston to limit

flows and to contain hazardous materials in the event of an accidental discharge.

2. Additional field studies should be conducted along the Neches River, Brazos River, Caney Creek, Colorado River, and Arroyo Colorado to define the source of the nutrients and metals entering the waterway.
3. Detailed hydrological and ecological studies should be conducted at several locations in land-cut areas to evaluate the impact of the existing waterway on the groundwater and surface hydrology.
4. Studies should be conducted on promoting bottom vegetation in shallow bays.
5. Current patterns in adjacent shallow bays should be considered when planning modification to the waterway.
6. Model studies should be conducted of proposed waterway modifications in shallow bays to optimize circulation patterns, control salinity levels, and reduce maintenance dredging.

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CHAPTER 1

INTRODUCTION

The Gulf Intracoastal Waterway (GIWW) extends along the coast of the Gulf of Mexico from Florida to Texas, serves as a navigable channel for shallow draft vessels, primarily barges and towboats, and offers a shortened and protected route between major ports. As shown in Figures 1, 2, and 3, the Texas section begins at the Sabine River and parallels the coast through eighteen counties to Brownsville, Texas, a distance of 424 miles (682.2 km). The authorized minimum cross-sectional dimensions at mean low tide are a depth of twelve feet (3.66 m) and bottom width of one hundred twenty-five feet (38.1 m). Authorized dimensions are the dimensions to which the channel is dredged; however, these are frequently not the existing dimensions because of over-dredging and shoaling. Deviations from the authorized minimum dimensions include barge mooring and turning basins, and locations where the GIWW crosses or runs concurrent with other, deeper channels.

The cost of the waterway from Apalachee Bay, Florida to Brownsville has been less than $300 thousand per mile. This is remarkably low when compared with other waterways such as the Illinois which cost $8.1 million per mile and the upper Mississippi which at places cost $7.2 million per mile. About $19.3 million was spent on all waterways of Texas in 1970, of which only $2,528,000 was spent on the Gulf Intracoastal Waterway, Texas Section. Of this amount $5,000 was for new work and the remainder for maintenance. The GIWW boasts a benefit to cost ratio of 26 to 1.

Objectives

The purpose of this study is to identify potentially adverse environmental

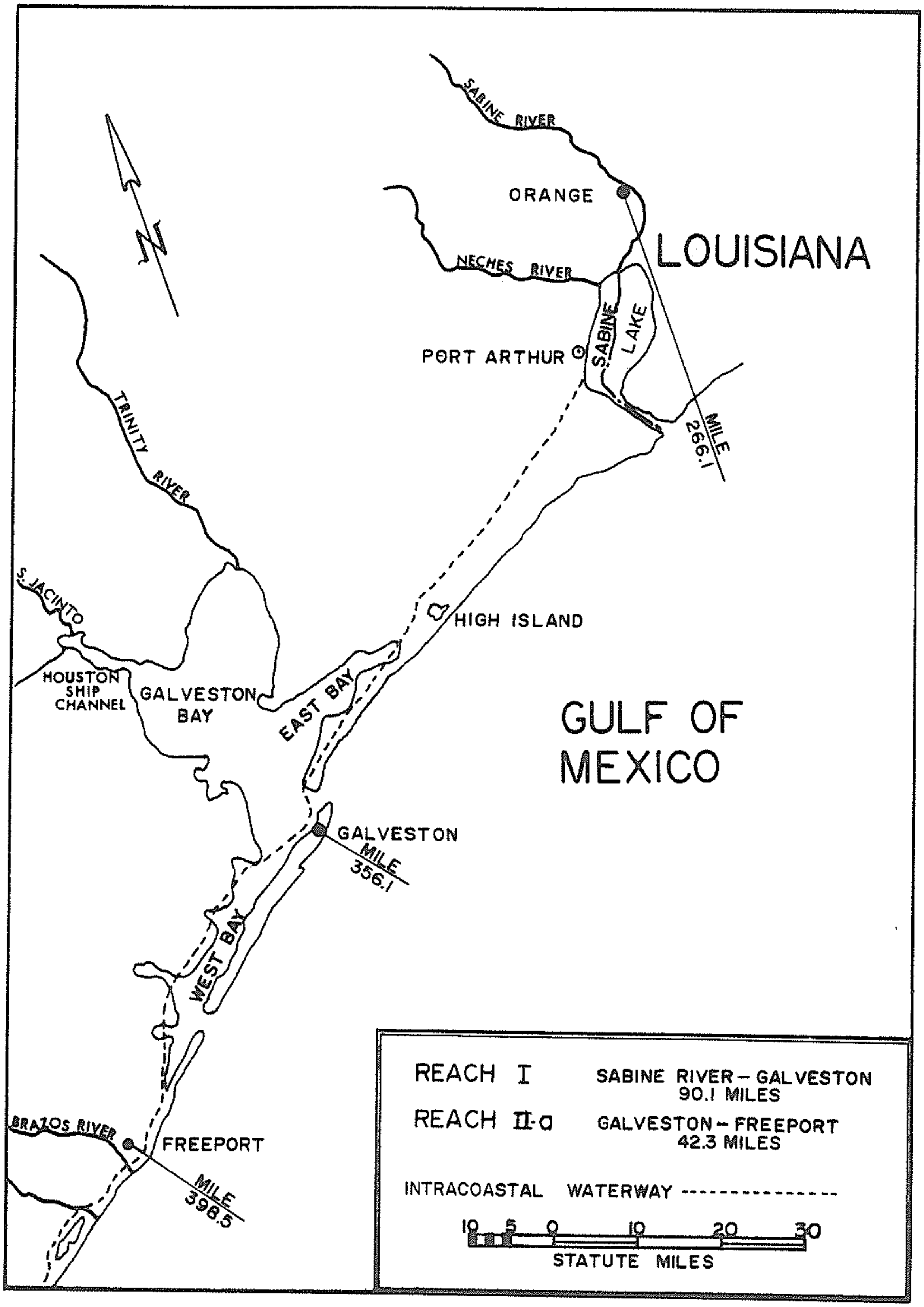

Figure 1. North Section of the Intracoastal Waterway

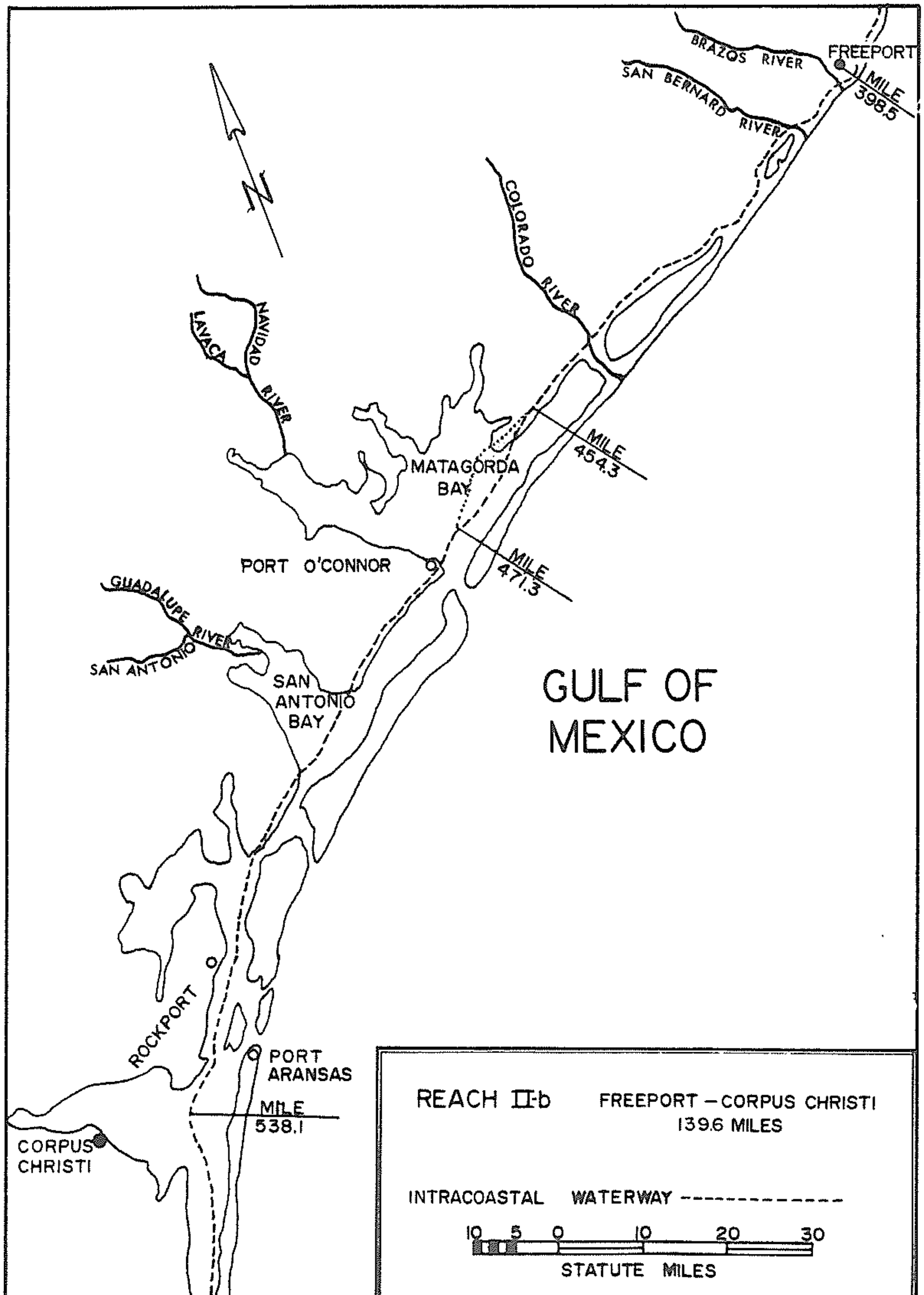

Figure 2. Central Section of the Intracoastal Waterway

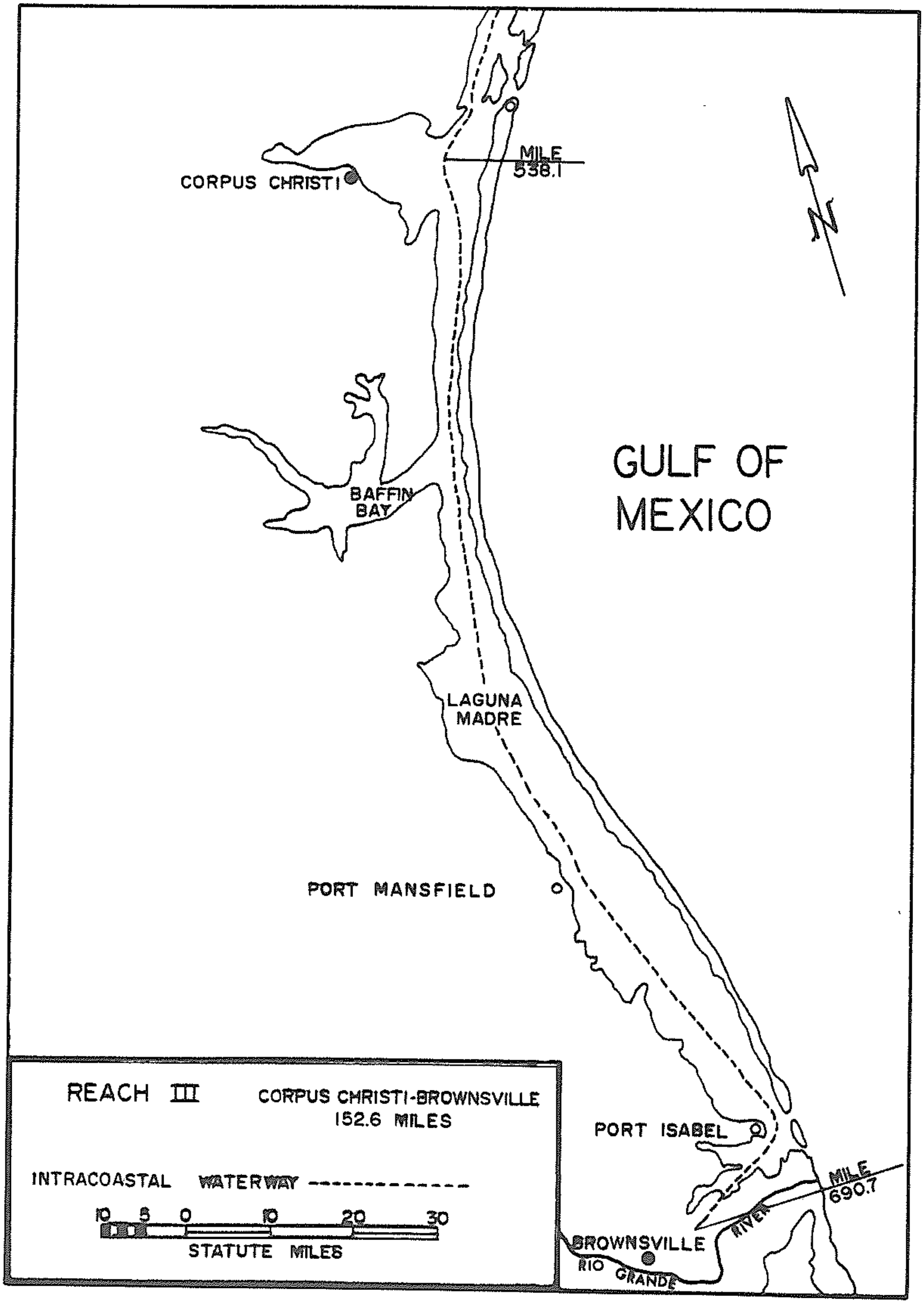

Figure 3. Southern Section of the Intracoastal Waterway

factors (except dredging) associated with the operation and maintenance of the Texas Gulf Intracoastal Waterway. The environmental considerations of dredging were not included in the study as this subject would be a major undertaking by itself and the Corps of Engineers is conducting studies on the environmental effects of dredging. The specific objectives of this study are:

1. to inventory existing physical, chemical and biological information concerning the waterway,
2. to conduct field sampling programs of physical and chemical water and sediment quality at critical locations along the waterway,
3. to evaluate the water and sediment quality of the present intracoastal waterway and to identify environmental problem areas related to operations and maintenance of the facility, and
4. to develop environmental recommendations for implementation by various agencies concerning the operation and maintenance of the existing waterway.

History

The inception of the Gulf Intracoastal Waterway was the result of an act of Congress in 1828 when $18,000 was appropriated for construction of a channel from Mobile Bay to Mississippi Sound.

With Texas recovery from the Civil War came the beginning of the Texas Section of the Gulf Intracoastal Waterway in 1874. In that year a shallow draft channel was constructed between Aransas and Corpus Christi Bays. In the years that followed a number of other small shallow draft channels were constructed by both public and private interests. In 1892, with the aid of federal funding the channels were connected to create a continuous passage five feet (1.52 m) deep and forty feet (12.19 m) wide. In 1925 authorization was given to increase the authorized channel dimensions between the

Sabine-Neches Waterway and Corpus Christi to a depth of nine feet (2.74 m) with a bottom width of 100 feet (30.48 m). By 1941 the waterway extended as far as Brownsville, Texas, ostensibly justified by national defense requirements. In 1949 the authorized dimensions were increased from nine (2.74 m) to twelve feet (3.66 m) in depth and the bottom width from 100 (30.48 m) to 125 feet (38.1 m). An alternate channel across south Galveston Bay between Bolivar Peninsula and Galveston Causeway was completed in 1954, and in 1960 the main channel between Aransas and Corpus Christi Bays was rerouted along the northwest shore of Redfish Bay.

An authorized relocation of the channel at the entrance to Matagorda Bay would return the channel to its former location. This proposed relocation is between mile number 454.3 and 471.3 as detailed on the map for this reach in Figure 2. It was moved during World War II to protect navigation on a portion in the northeast part of the bay. The relocation to its original route would provide safer passage for barge traffic because of the greater length of land cut and better alignment of the prevailing winds.

Facility

The waterway traverses bays or follows land cuts for the entire length of the Texas coast. There are fifteen bridges across the channel as well as numerous submerged pipelines and cables, and overhead cables. Ten barge mooring and turning basins are associated with the waterway. For administrative and computational purposes the waterway is divided into three reaches as indicated on the maps, Figures 1 through 3. Locks are necessary where the channel crosses the Colorado River. They also prevent refuse and sediment from entering the waterway. Floodgates at the Brazos River accomplish nearly the same function. For the location of waterway structures see Appendix A.

Texas has twenty-four ports, eleven of which serve deep-draft vessels. All of the ports are serviced either directly or indirectly by the GIWW. During 1970 over thirty-one percent of the Texas population was concentrated in the thirty-six Coastal Zone counties; eighty percent of this population is urban.

In 1967 there were 251 chemical and allied products establishments in the coastal region. They employed over 33 thousand people with an annual payroll of $318.4 million. An economic impact statement prepared by Miloy and Phillips (1974) of the Texas Engineering Experiment Station at TAMU indicated a total economic value of $6.0 billion for the chemical and allied products industry. The same study reported 62 establishments associated with petroleum refining employed 27,300 people with an annual payroll of $251.6 million. The total economic value of this industry was $10.7 billion. Additionally mining in the coastal counties has an economic value of $2.1 billion of which $41.3 million is attributable to the shell industry, $64.9 million to non-metallic minerals, and $2.0 billion to petroleum extraction. The three industries employ an additional 15.8 thousand people, 13.9 thousand of which are involved in petroleum extraction. It is justifiable to attribute at least a portion of this economic impact to the presence of an economic means of transportation.

The GIWW is primarily a shallow draft channel designed to accommodate standard size barges as detailed in Table 1; however, the waterway is at places integrated into major ship channels and in such places the dimensions of the channel are sufficient to accommodate ocean vessels and the new super barges described in Table 2. Considerations other than channel depth and width include horizontal and vertical clearances of bridges, locks, and flood gates along the waterway. Tow lengths are variable but are generally

Table 1. Barge Sizes

Length (feet)	Breadth (feet)	Draft* (feet)	Capacity (tons)
	Open Hopper Barges		
175	26	9	1000
195	35	9	1500
290	50	9	3000
	Covered Dry Cargo Barges		
175	26	9	1000
195	35	9	1500

* Draft is the distance from water level to the lowest part of the vessel under water. Channel depth for slow vessels must be three feet greater than the vessel draft, and for better efficiency and faster speeds the depth must be at least five feet greater.

Source: Miloy, J. and Phillips, C., Primary Economic Impact of the Gulf Intracoastal Waterway in Texas, 1974, TAMU-SG-74-211, p. 100

Table 2. Selected Super Barges in Service

Type Barge	Dimensions (feet)	Deadweight (tons)	Number in System
Dry Cargo	420 X 80 X 34	15,000	3
Converted Liberty Carriers	441 X 56 X 37	11,700	4
Open Deck Cargo	360 X 75 X 25	10,000	2
Log Carrier	364 X 80 X 23	9,400	1
Dry Bulk	420 X 80 X 36	17,000	1
Covered	356 X 78 X 22	7,200	3

Note: Use of these barges is restricted to major ship channels presently.

restricted to four barges and one tug boat. The size of tows using the locks at the Colorado River crossing or passing through the Brazos River floodgates is limited by the respective dimensions of those facilities.

Operation

Almost three-fourths of Texas' goods by weight are transported by water and the Gulf Intracoastal Waterway is the primary carrier. In 1973 inland waterways in the United States carried 358 billion ton-miles of traffic: 126 billion on the Great Lakes, 155 billion on the Mississippi River System and 77 billion on the coastal systems. Of this last figure, 5 billion ton-miles were on the Texas Section of the Gulf Intracoastal Waterway. In 1970 water transportation had an economic impact in Texas of $615 million with water transportation services adding $132 million. During this period Texas waterways carried 73.8 percent of all the state's tonnage and 15.9 percent of commodities other than coal or petroleum.

The Texas Section of the Gulf Intracoastal Waterway carried approximately 63 million tons of waterborne commerce in 1973. As shown in Figure 4, the reach from the Sabine River to Galveston carried 63.1 percent of this while the reach from Galveston to Corpus Christi carried 32.8 percent. Only 4.1 percent was carried in the reach from Corpus Christi to Brownsville. The percentage of commodities by reach are shown in Figure 5. Nonmetallic minerals and un-manufactured shells accounted for 17.7 percent of the volume, crude petroleum 25.2 percent, chemicals and allied products 20.8 percent, petroleum and coal products 30.4 percent, and all others account for the remaining 5.9 percent.

In 1973 there were 28,856 eastbound trips and 29,196 westbound trips by commercial vessels in Reach I. Reach II had 23,888 and 24,145 respectively while Reach III accommodated 16,630 eastbound trips and 16,633 westbound

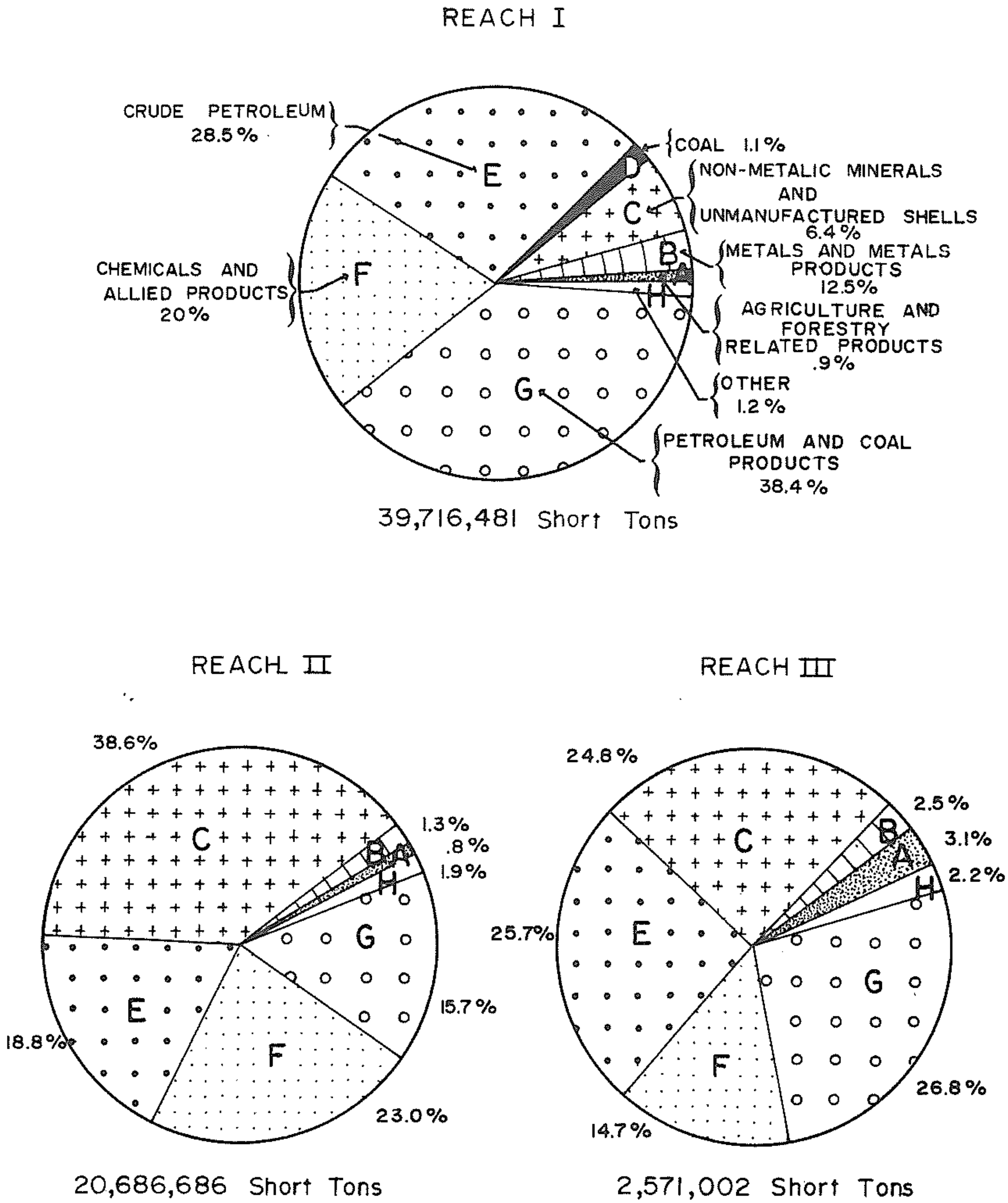

Figure 4. Percent Tonnage on the Intracoastal Waterway

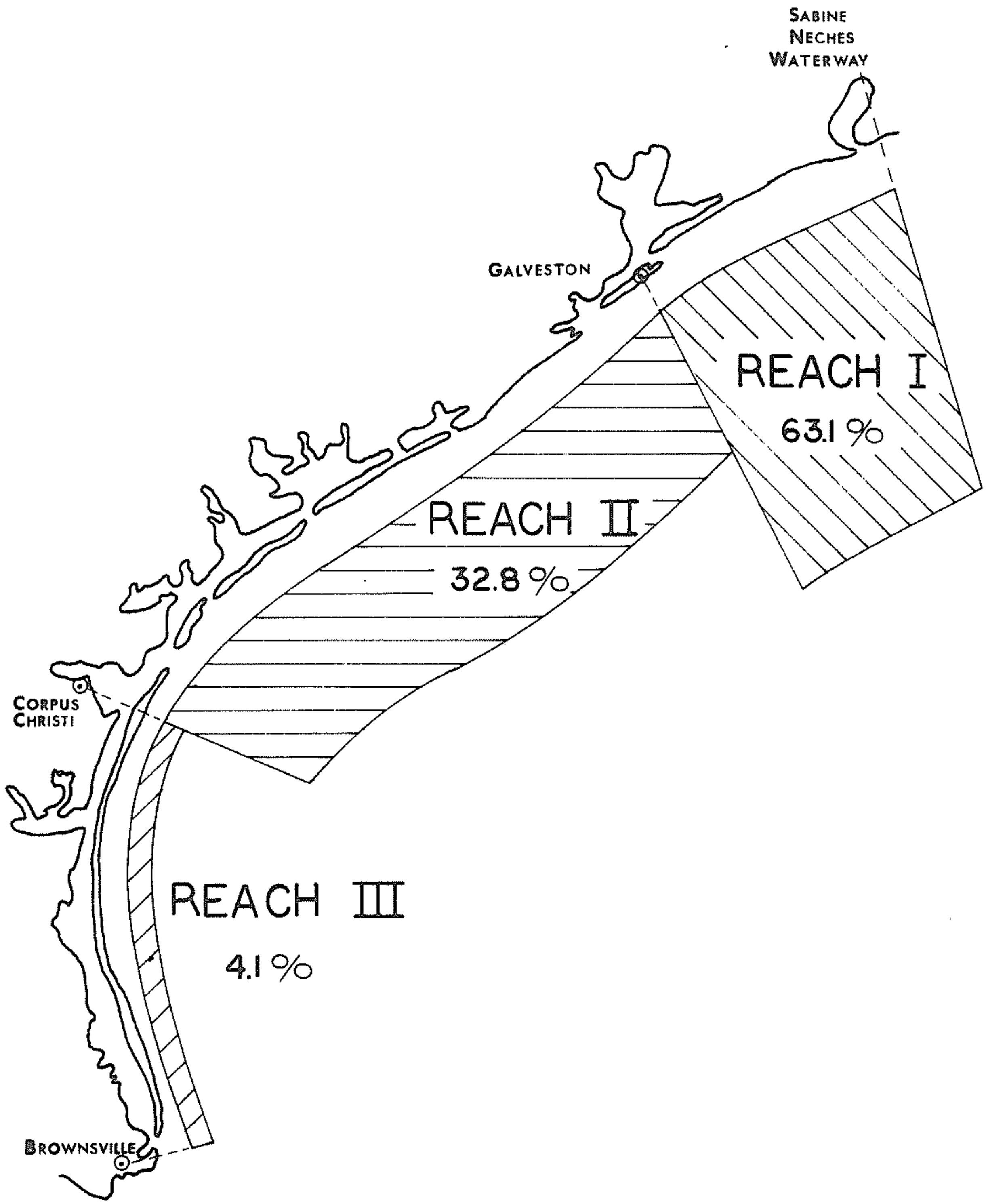

Figure 5. Percent Commodities by Reach

trips. The total number of vessel trips on the Texas Section of the Gulf Intracoastal Waterway for 1973 was 139,238 (see Appendix B).

Although the Gulf Intracoastal Waterway was primarily designed to facilitate commercial transportation, it is also used by pleasure craft and has therefore enhanced the recreational value of the coastal zone. There are no complete figures available to show the extent of this utilization on the entire waterway. The waterway may be useful in the shorter land cut regions where it connects bays which may be utilized for recreational purposes.

Maintenance

The United States Army Corps of Engineers, under the authority of House Document No. 238, 68th Congress, has federal responsibility for the Gulf Intracoastal Waterway. The Galveston district has responsibility for the Texas Section of the waterway. Major activities under this responsibility include approving structures across the channel, dredging, and investigating proposed changes, along with maintenance of the Colorado River locks and the Brazos River floodgates.

Under the provisions of the recently adopted Texas Coastal Waterway Act of 1975, the Texas Highway Commission assumes local sponsorship for the Gulf Intracoastal Waterway. Responsibilities as local sponsor include maintenance and construction of bridges over the channel and provision of rights of way and dredged material disposal areas. The United States Coast Guard is responsible for the maintenance and placement of buoys along the channel.

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2. Miloy, J. and Phillips, C., 1974. Primary Economic Impact of the Gulf Intracoastal Waterway in Texas, Sea Grant Program, TAMU-SG-74-211.

3. Phillips, C., 1974. Indirect Economic Effect from Gulf Intracoastal Waterway Commerce in Texas, Sea Grant Program, TAMU-SG-74-218.

4. U.S. Army Corps of Engineers, 1974. Maintenance Dredging, Gulf Intracoastal Waterway, Texas Section, Draft, Volume 1.

5. U.S. Department of Commerce, Nautical Charts.

Chart No.	Edition	Date
885-SC (N.O. 11098)	2	October 1973
887-SC (N.O. 11058)	7	December 1973
889-SC (N.O. 11057)	7	December 1973
891-SC (N.O. 11056)	7	February 1974
11314 (892-SC)	5	September 1974
11308 (893-SC)	5	August 1974
895-SC (N.O. 11046)	5	June 1974
896-SC (N.O. 11042)	5	June 1974
897-SC (N.O. 11043)	5	June 1974
898-SC (N.O. 11055)	5	June 1974

CHAPTER II

ENVIRONMENTAL BACKGROUND INFORMATION

This chapter describes the physical, cultural and land use capability units along the Gulf Intracoastal Waterway.

Physical Characteristics of the Texas Coast

Climatology

The climate of the Coastal Zone is in general subtropical with long warm to hot summers and short mild winters. The average annual temperature shows a fairly regular decrease with latitude from about 74 degrees F (23.3 degrees C) at Brownsville near Mexico to about 70 degrees F (21.1 degrees C) at Sabine Pass in the northeast section of the coast. The average precipitation varies from about 26 inches (660 mm) at Brownsville to about 55 inches (1397 mm) at Sabine Pass. Predominant winds are from the north during the winter months and from the southeast or south in the summer.

Since the midwestern plains extend to Canada without major topographic relief, cold winds from the Canadian Arctic come to the Texas coastal waters with great frequency and regularity during the winter months. It is not uncommon to have a temperature change of 40 degrees (22.2 degrees C) within a couple of hours. The region has also been marked by extreme flood conditions, interspersed with prolonged droughts throughout the recorded history.

The climate in the area from Sabine to Galveston (Reach I) is primarily a wet subtropical region. The mean annual temperature ranges between 69 and 71 degrees F (20.6 and 21.7 degrees C) and average rainfall ranges from 38 to 55 inches (965 to 1397 mm) per year.

The climate in Reach II (Galveston to Corpus Christi) is a product of the combined effect of the humid subtropical region to the northeast, the semi-arid region to the west and southwest, and the warm moist influences of winds from the Gulf of Mexico. The mean annual temperature ranges from 70 to 72 degrees F (21.1 to 22.2 degrees C), and the average annual rainfall ranges from 30 to 38 inches (762 to 965 mm).

In the section from Corpus Christi to Brownsville (Reach III), the climate is semi-arid and is characterized by tropical temperatures with a mean annual range from 72 to 74 degrees F (22.2 to 23.3 degrees C) and low rainfall which ranges from 26 to 30 inches (660 to 762 mm) per year. The climate is characterized by high rates of evaporation which combined with naturally restricted water circulation and minimal freshwater inflow results in hypersalinity in the Laguna Madre.

Shore Features

The entire Texas coast presents an extremely low profile. The only noticeable relief along the coast is High Island which is the surface expression of a large salt dome and rises some 50 feet (15.24 m) above the low coastal plain. Perhaps the most important shoreline features are the inlets or passes which break the barrier shoreline at frequent intervals. The largest and deepest of these passes are Sabine Pass, Bolivar Pass at Galveston, San Luis Pass at West Galveston Bay, Pass Cavallo at Matagorda Bay and Aransas Pass at Port Aransas. Pass Cavallo and San Luis Pass are not maintained as a channel, and therefore have shifting sand bars. Sabine, Bolivar and Aransas Passes are maintained as major channels and have controlling depths of 40 feet (12.19 m). Several attempts have been made to create new passes in order to maintain high marine animal populations inside the bays.

Surface Geology

The surface geology of the Texas coast is separated mainly into Holocene and Pleistocene. Soils of the Texas coast are generally deep and range from very permeable, excessively drained sands to nearly impermeable, very poorly drained clays. Some of the soils are saline coastal sands flooded by Gulf tides and subject to wind erosion. Sticky, wet, saline soil characterizes the marshes. A large portion of the soil located in the upper half of the coast is fertile and highly productive. The areas of low fertility include the sandy soils along the southern half of the coast, the offshore islands, and some pine-timbered areas.

Freshwater Resources

Along the Texas coast several major rivers empty directly into the Gulf through long, narrow, straight estuaries with low natural levees. The Brazos, Colorado and San Bernard Rivers all have about seven-mile estuarine channels with about the same width and depth leading into the sea even though each has a different characteristic river discharge. The estuarine environments provided by such long, narrow channels are relatively poor for either recreation or as animal and plant habitats.

The Sabine, Neches, Trinity, San Jacinto and Guadalupe-San Antonio Rivers account for most of the freshwater discharge along the Texas coast through bays and estuaries. The Sabine and Trinity Rivers have the highest consistent discharge, since they drain wet or humid regions. Although it has the largest drainage basin, the Rio Grande flows through an arid zone and most of its runoff is retained in large reservoirs upstream. This, however, is not limited to the Rio Grande as much of the runoff for rivers in Texas is being retained in upstream reservoirs.

The Brazos, Trinity and Sabine Rivers carry the most sediment into the coastal area. The Sabine, Neches, and Trinity carry mostly fine sediments to the coast and do not supply significant volumes of sands to the beaches and shores. The Brazos, Colorado and intervening rivers southward to the

Rio Grande carry larger percentages of sandy materials, and during flood periods contribute considerable sand to the Gulf and its shore processes.

Most areas along the Gulf coast are underlain by little freshwater but large quantities of slightly and moderately saline ground-water are present in all areas. In general the fresh ground-water potential in most of the areas is fully- or over-developed. Especially in the northern part of the coast, water levels have declined and salinization of water in the aquifers has occurred.

Bays and Estuaries

Bottom Features

Texas bays and estuaries are shallow and with relatively uniform shoreline configuration. Most grade smoothly toward a slight depression in the center. Only a small portion of Sabine Lake exceeds six feet (1.83 m) in depth. Galveston Bay is also shallow, although most of the central portion is between 6 and 12 feet (1.83 and 3.66 m) deep. West Galveston Bay and East Matagorda Bay are quite shallow, seldom exceeding four or five feet (1.22 or 1.52 m). Matagorda Bay has a relatively deep southwestern area reaching 13 to 14 feet (3.96 to 4.27 m) deep while most of Espiritu Santo, San Antonio, St. Charles and Copano Bays average 3 to 6 feet (1.83 m) deep. Corpus Christi Bay is one of the deepest bays and a large portion exceeds 12 feet (3.66 m). In the Laguna Madre depths do not exceed 12 feet (3.66 m) and average less than 6 feet (1.83 m).

Sediments which now cover the bottom of the estuaries have been distributed primarily by winds in the Laguna Madre, by currents in the central bays, and through river discharge and runoff in the humid, high rainfall region to the northeast.

Temperature Regions

Air temperatures are important along the Texas coast in that estuarine waters are usually so shallow that they are well mixed and thus bottom water reflects air temperature changes rapidly. Consequently, the estuarine waters are warmer than the Gulf waters during the summer months and colder in the winter. Average temperatures in the bays and estuaries vary from the range of 50 to 60 degrees F (10 to 15.6 degrees C) in January to 80 to 90 degrees F (26.7 to 32.2 degrees C) in August.

Salinity Characteristics

Because of the extreme variations in climate, large variations of salinity occur in bays along the southern coast. It is here that salinities may rise to 40 to 50 parts per thousand (ppt) during the summer and drop to almost zero during hurricane floods. The "Hole" in Laguna Madre near Baffin Bay shows the greatest salinity variation on the coast, ranging from 5 to 120 ppt. In the lower Laguna Madre, after the construction of the GIWW and Port Mansfield Channel salinities range between 5 and 60 ppt while other portions of the Laguna Madre have a smaller range of salinities. Salinity fluctuations range from 16 ppt in the Galveston Bay system to over 30 ppt in the Coastal Bend estuaries. The maximum salinity seldom exceeds 32 ppt in Galveston Bay. Sabine Lake has salinities below 14 ppt much of the time.

Tidal Characteristics

Because most of the bays along the coast have restricted openings to the Gulf, responses to tidal changes taking place on the open coast are considerably dampened within the estuaries.

The astronomical tides are of the mixed type with one low and one high per 24-hour period with a maximum range of about three feet (0.91 m), and with two highs and two lows per 24-hour period with minimum range of less than 0.5 feet (0.15 m). The estuarine tidal ranges are very small and occur one to five hours later than the corresponding high for the Gulf side. They also lack normal periodicity.

The significant tides are those created by winds. This is especially true for hurricane winds, which may raise tidal levels as much as 15 feet (4.75 m) and virtually empty some bays. During winter storms, wind tides range up to four or five feet (1.22 or 1.52 m). Likewise, when the strong southeast trade winds blow for a prolonged period, water levels build up within the bays.

Current Patterns and Longshore Drift off the Texas Coast

More data are available on wind speed and direction than on actual current directions. It is the winds, for the most part, which drive the currents. The little available existing data indicate that water does not move in a single direction along the entire coast but that currents along the coast reverse. Water often flows to the north at the lower end of the Laguna Madre and southwest along the upper coast.

Estuarine Circulation

Each of the estuaries has circulation patterns which are primarily influenced by the prevailing wind directions. Consequently, circulation is quite different between north and south winds.

Cultural Characteristics

Large expanses of the coast are sparsely populated and are used primarily as cropland or grazing land. There are numerous parks and recreational areas which account for a total of 213 sq. miles (551 sq. km). Areas of major industrial development are population centers and therefore are also regions of major concern. Industries have a major impact on the coastal zone, both as a source of employment and their effect on the environment.

Land Use

Land use adjacent to the Gulf Intracoastal Waterway is fairly consistent for large areas varying from rangeland in the Laguna Madre to urban-industrialized around Corpus Christi Bay. A region of marsh rangeland begins in the vicinity of Matagorda Bay and continues to within a few miles of Galveston Bay, with the exception of the area between the forks of the Brazos River which is urban-industrialized. The lower shore of Galveston Bay is urban-industrialized with marsh rangeland resuming predominance at Bolivar Peninsula and continuing with intermittent pastureland to Port Arthur, which is again an urban-industrialized region. North Sabine Lake is marsh rangeland and irrigated cropland. The margins of all these areas are generally sparsely populated and may be classified as either dry or irrigated cropland, rangeland, pastureland, forest, and marsh rangeland.

Recreation

The recreation and wildlife areas in the coastal zone provide such activities as photography, hunting and fishing, swimming, boating, surfing and diving. There has been resort development along Padre Island and Mustang Island.

Sportfishing is not limited to a particular portion of the coast. However, it is especially popular at Galveston, Freeport, Port Aransas and Port Isabel. Many species of finfish are attracted to the drilling platforms and submerged vessels and structures along the coast and these areas provide generally good sportfishing.

Commercial Fishing

Commercial fishing along the Texas coast is a multimillion dollar business ($70 million for 167 million pounds (75 m tons) in 1971). The commercial shrimp (primarily brown and white), the commercial oyster, the menhaden, the blue crab, and the common sportfish are the most important species economically on the Texas coast. Some of the more common sportfish include gafftopsail catfish, Atlantic spadefish, seatrout, Atlantic croaker and the less common but popular southern flounder and broad flounder. Almost all species are dependent upon bays and estuaries for breeding and nursing grounds. A high number of juveniles may be located in these areas. Records indicate the Galveston Bay, Trinity Bay, and Sabine Lake accounted for well over 80 percent of the annual oyster crop in 1971. Matagorda Bay also generally produces a good crop. The open Gulf accounts for by far the largest catches of finfish but the Laguna Madre reach accounts for almost 25 percent of the total landings and 30 percent of the coastal region production.

Land Use Capability Units along the Waterway

Land use capability units along the Gulf Intracoastal Waterway are summarized in Table 3 and described in detail in the following section. Maps showing the location of the capability units are included at the end of the section. Symbols on the maps refer to land use capability units described in the following section. Waterway mileage referenced in the following discussion is also shown on the maps.

Bays, Lagoons and Estuaries

According to the University of Texas report on Management of Bay and Estuarine Systems (Fruh, et al., 1972) bays, lagoons and estuaries are water masses which occupy river valleys and elongated areas between barrier islands and mainland. These water masses are transitional physically, chemically and biologically between river and lake systems and the open marine environment. Shifting and sometimes subtle interfaces exist within the shallow water bodies, where changes can occur within the system. These areas in conjunction with the adjacent marshes are highly productive, delicately balanced ecosystems which are susceptible to external modification. Man can have a significant effect on these processes which may result in economic, aesthetic and cultural benefits or losses.

IA. River-Influenced Bay

River-influenced bay exists where a bay has been formed at the mouth of a river and is characterized by high turbidity from the suspended solids in the river discharge and low salinity due to dilution. The salinity will be variable depending on the amount of discharge. The depths in this area range from 3 to 7 feet (0.91 to 2.13 m) and the bottom sediments are primarily layered and mottled muds. A high concentration of nutrients due to river inflow and a low species diversity is usually exhibited. The turbid waters entering these areas from the rivers cause a decrease in light penetration and thus reduce photosynthetic activity. Also the discharge from the river is usually high in humic acids causing low pH values. The turbidity, low salinity and low pH values make the area undesirable for growth of oysters and other sessile benthonic shellfish. However, these conditions are favorable for the development of shrimp in the juvenile stages.

Areas which are characterized by these features include the northern part of Sabine Lake, Dollar and Dickinson Bays above Texas City, Matagorda Bay at the mouth of the Colorado, north Tres Palacios Bay and Oyster Lake, northern Hynes Bay, north St. Charles Bay and Nueces Bay which is the southernmost example of this type region.

IB. Enclosed Bay

Enclosed bay is the area of the bay that is influenced little by neither river nor tidal currents. Circulation is generally poor and there is an abundance of fine sediments due to the reduced velocity of the waters. There is a low species diversity and large numbers of individual organisms. The depths range from three to eight feet (0.91 to 2.44 m). Due to poor circulation, high or low salinity extremes are often reached in these areas. The benthonic organisms are mainly infaunal feeders which burrow through the sediments to produce mottled, organic-rich muds. The common living species in the area is the clam.

The enclosed bay is typical of the middle portion of Sabine Lake (approximate mileage 280-285) East Bay, Chocolate Bay north of the Intracoastal Waterway, Bastrop and Christmas Bays, Chocolate Bay (West Lavaca Bay), Shoalwater Bay, the lower portion of St. Charles Bay, Copano Bay, Oso Bay and several bays in the sandflats between Port Mansfield and the Arroyo Colorado.

IC. Reef and Reef-Related Areas

Reef and reef-related areas contain submerged mounds and elongated ridges with adjacent areas containing oysters and associated reef organisms. The only exceptions are the reefs in Baffin Bay which are exclusively serpulid and are now dead. The reefs are ridged structures that locally restrict circulation and are commonly positioned perpendicular to prevailing currents. The reef areas serve as valuable feeding grounds for many varieties of game and commercial fishes. The majority of the reef is composed of dead oyster shells, but epifaunal, nektonic and some vagrant benthonic organisms are also found on the living reef surface.

Reef and reef-related areas include dispersions throughout the western portion of East Bay north across the central portion of Galveston Bay to a point just above Texas City and again just below the Texas City Ship Channel. Several reef areas are located in East and West Matagorda Bays. Espiritu Santo Bay and San Antonio Bay abound with reefs and related areas, some of which are quite large. Other reef areas occur along the waterway as indicated on the maps.

ID. Grassflats

Grassflats are shallow subaqueous flats, ranging from 1 to 5 feet (0.3 to 1.52 m) deep, located principally along the margins of bays and lagoons. The grassflats are characterized by moderate to dense growth of marine grasses. The dense grass helps to maintain temperatures in a range suitable for many organisms. The areas are feeding grounds for a number of game and commercial fish along with a number of other animals.

Some of the more prominent examples of grassflats include the northshore muds of Redfish Bay and either side of the Gulf Intracoastal Waterway from the Padre Island Causeway to Southbird Island, and either side of the canal from Port Mansfield to about mile 657. These areas are especially prevalent along the Laguna Madre.

IE. Tidal Inlet and Tidal Delta

Tidal inlets are channels connecting the bays with the open gulf or larger bodies of water. On the gulf end of the channel is the flood tidal delta and on the other end is the ebb tidal delta. These are depositional areas associated with the sediment transport through the tidal inlet. The inlets are the passage way for fish migration and water exchange. During periods of flooding on the mainland a large amount of fresh water passes into the gulf and during hurricanes a significant amount of marine water is passed into the bay or lagoon.

IF. Open Bay

Open bay areas are located in the lower end of the bay where tidal influence is large. The depths range from 6 to 12 feet (1.83 to 3.66 m) and circulation is good. The substrates are generally mottled mud. Species diversity is relatively high with the number of species increasing and the number of individual organisms decreasing as the salinity increases. The normal range of salinities is from 20 to 30 ppt.

Matagorda Bay, the western end of West Bay and Corpus Christi Bays are also good examples of open bays.

IG. Enclosed Hypersaline Bay

Enclosed hypersaline bays are similar to enclosed bays but possess the additional characteristic of high salinity. This high salinity (30-80 ppt) is due primarily to a combination of low rainfall amounts, high evaporation rates and poor circulation all of which are characteristics of the southern Texas coast. Species diversity is low and there is a small number of individual organisms due in part to the hypersaline conditions. The most commonly observed species include clams and snails. Water depths range from 4 to 12 feet (1.22 to 3.66 m).

IH. Sandflats

Sandflat areas occur on the backside of barrier islands south of St. Joseph Island and the landward side of Laguna Madre. This emergent-submergent area varies from 2 feet (0.61 m) above to 1 foot (0.3 m) below mean sea level. The flats are usually flooded by wind-driven bay or lagoon waters. They are predominately composed of sands with thin algal mats which bind the sediments into a tough substrate. High temperatures in the thin layer of water on the flats restrict biologic activity.

These areas occur in the vicinity of Corpus Christi Bay and south through the Laguna Madre. The area south of "The Hole" in the Laguna Madre is an excellent example of this capability unit.

IJ. Bay or Lagoon Margin

Bordering bays or lagoons are areas of high current activity and rapid sand transport. Depths range from 0-3 feet (0-0.91 m) with salinity and temperature being variable. These marginal areas support locally sparse marine grasses. Species diversity increases near the tidal inlets where the mixing of gulf marine water and bay water takes place. Great seasonal variation exists in the shallow bay-margin assemblages as the epifaunal and motile invertebrates migrate into deeper water during periods of extreme high or low temperatures or salinities.

The northern shore of Corpus Christi Bay and the opening to the Laguna Madre are both examples of a bay or lagoon margin. Other examples include the northwest and southwest shores of Matagorda Bay and the Matagorda Island side of Espiritu Santo Bay and San Antonio Bay.

IK. Subaqueous Sandflats

This area is similar to sandflats with the exception that it is inundated at all times with the water depth varying from 0-3 feet (0-0.91 m). This is typical of the area located south of Baffin Bay and "The Hole", in the northern part of Laguna Madre. Large changes in salinity and temperature are characteristics of the area. Salinity varies from 30 to 80 ppt and the temperature from 55 to 110 degrees F (12.8 to 43.3 degrees C).

IL. Restricted Hypersaline Bay or Lagoon Margin

Restricted hypersaline bay or lagoon margin areas are found along the borders of bays and lagoons south of Corpus Christi. They are away from tidal influence and have rare river input due to the small amount of rainfall in the area. The hypersaline condition results from the high evaporation rate and the rare fresh-water inflow. The salinity will vary from 5 to 80 ppt but the normal is greater than 30 ppt. The depths in these areas range to 6 feet (1.83 m) and temperature ranges from 55 to 110 degrees F (12.8 to 43.3 degrees C). The area has a low population of organisms associated with a correspondingly low species diversity. Sparse grass, clams and algae are the most common.

North of "The Hole" bordered by sandflats on the Gulf side and an enclosed hypersaline bay on the coastside is located a restricted hypersaline bay and lagoon margin. Baffin Bay and Alazan Bay are also bordered by this margin.

IM. Restricted Bay Center

Restricted bay center areas have physical characteristics similar to the restricted hypersaline bay margin. They are closed to tidal input and rarely are river-influenced. Temperature ranges from 55 to 110 degrees F (12.8 to 43.3 degrees C) and salinity ranges from 5 to 80 ppt with normal being greater than 30 ppt. The depth varies between 6 and 12 feet (1.83 and 3.66 m). The bottom is euxinic and in the deeper parts laminated muds. These areas display a low species diversity and small number of individual organisms, due in part to the hypersaline conditions.

IN. Fresh to Brackish Water Bodies

Fresh to brackish water body areas include land-locked lakes, ponds and reservoirs, exhibiting variable substrate with inland areas containing fresh water and coastal units temporarily brackish or saline water.

Land-locked water masses of this nature are abundant in the Port Arthur area, but may be found along almost any sector of the coast.

Major River Systems

Through-flowing streams and their associated lakes and sloughs, point-bar sands, and floodplain muds and silts are included in this category; excluded are headward eroding streams which originate within the coastal plains. The valleys are filled with point-bar sands and floodplain muds and silts, but except for the Colorado, Brazos and Rio Grande, these incised valleys have not been entirely filled by alluvial sediments.

IIA. Fluvial Woodlands

Fluvial woodland areas are made up of silty clay, silt and sand substrate. In the southern part of Texas along the Rio Grande there are diverse assemblages of trees, shrubs, vines and local areas of palm groves. Further north, along the Brazos, Colorado and San Bernard River Systems, the fluvial woodlands are composed of water-tolerant hardwoods including pecan, hickory, live oak, elm, hackberry, magnolia, sweetgum, red haw, ash and shortleaf pine. The areas are subject to seasonal floods.

IIB. Fluvial Brushland

Fluvial brushland areas are composed of sand and silt substrate and are occasionally flooded. They are vegetated by dense mesquite, chaparral, ebony, brazil, guayacan, althorn, cactus and sparse grasses. The area is extensively cultivated.

Locations with these characteristics dominating are the Rio Grande Floodplain and the Arroyo Colorado Floodplain.

Coastal Wetlands

IIIA. Saltwater Marsh

Saltwater marsh areas are flooded daily by tidal action and contain plants such as cordgrass, glasswort, seep weed and sea oxeye. Saltwater marshes, as are the brackish to freshwater and brackish-water, are areas of high organic productivity and are a fundamental nutrient link in the bay and estuary system. Common inhabitants include mammals and fowl.

Saltwater marshes are commonly found along the Texas coast north of Baffin Bay on the back sides of barrier islands and along the margins of ancient as well as presently active deltas.

IIIB. Brackish to Freshwater Marsh

Brackish to freshwater areas grade into salt marshes and contain plants such as coastal sacuhuista, marshy cordgrass, big cordgrass, bullrush, cattail and rushes. Common inhabitants of these areas are snakes, mammals and fowl.

Good examples of this land use capability unit are along the Sabine-Matagorda reach of the waterway.

IIIC. Brackish-water Marsh

Brackish-water marsh areas are low and perennially wet. These marshes are supplied with salt water from storms and fresh water from rainfall and runoff. Vegetation in the area includes saltgrass and rushes and is inhabited by mammals and fowl.

As might be suspected brackish-water marshes are frequently associated with freshwater marshes and often grade into them. Examples of such occurrences exist between the waterway and the gulf from Sabine Lake to

Galveston Bay.

Coastal Plains

Occuring landward from water masses are coastal plains or flat uplands which extend from sea level to an elevation of approximately 100 feet (30.48 m). Topographic relief is generally slight with most local relief being produced by headward eroding streams and salt domes. The coastal plains are underlain predominantly by ancient deltaic, fluvial and barrier-strandplain sediments. Most of these areas are traversed by elongated sand belts.

IVA. Prairie Grassland

Prairie grassland area consists of flat to gently rolling uplands with prairie grasses and mud and sand substrate. Much of the area commonly contains bluestem, indiangrass, sparse mesquite, hackberry, huisache, chaparral and cactus. Animal inhabitants in the area include fowl and small animals.

Characteristic of many portions of the coast, these grasslands may be found very close to the waterway on land-cut regions such as the reach between Sabine Lake and Galveston Bay and the reach bordering East Matagorda Bay and Matagorda Bay.

IVB. Loose Sand and Loess Prairies

Loose sand and loess prairie areas are commonly overgrazed and have scattered oak mottes. Freshwater marshes appear in blowouts and depressions in wet cycles. Inhabitants in the area include rodents, mammals, snakes and fowl.

Loose sand and loess prairies are a dominant feature below Corpus

Christi Bay bordering the Laguna Madre to the Baffin Bay region.

IVC. Intense Wind Deflation

Areas of wind-tidal-sand activity cause sand sheet erosion. Salt-tolerant grasses on small unmapped clay dunes are found along with algal mats.

Areas of intense wind deflation occur with frequency below Baffin Bay and on the landward side of the canal bordering the sand flats.

IVD. Saline Grasslands

Saline grassland areas are located along the southern part of the Texas Coast near Brownsville. They are vegetated by coastal sacahuista, other salt-tolerant grasses and alkali weeds. The inland saline grasslands grade into brush-covered bottomlands and fluvial brushlands. The coastal areas grade into saltwater marsh.

<u>Made Land and Disposed Dredged Material</u>

Made land areas are composed of dredging sediments used to fill shallow bay areas and wetlands for increased land utilization. This fill material exhibits highly variable physical properties. Disposed dredged material is the waste sand, mud, and shell emptied into bays or adjacent lowlands during dredging operations and oyster shell production. The margins of these dredged material islands are highly susceptible to wave and current activity.

VA. Made Land

Made land areas are composed of dredged sediments used to fill shallow bay areas and wetlands for development and industrial purposes. The sediments (sand, mud and shell) come from barrier, marsh and delta areas and have highly variable physical characteristics.

VB. Subaerial Disposed Dredged Material

These areas are composed of waste sand, mud and shell dumped into bay or adjacent lowlands during channel construction. The material usually forms islands elongate to circular in shape and protruding up to 20 feet (6.2 m) above mean sea level.

Subaerial and subaqueous material occur almost the entire length of the waterway with the distinguishing factor being elevation. The land-cut region on map sections A-A to B-B contains a continuous subaerial dredged material site parallel to the waterway.

VC. Subaqueous Disposed Dredged Material

Subaqueous dredged material sites are areas of mixed substrate along dredged channels and near dredged oyster shell beds. Sediments are commonly poorly sorted sand, silt and mud. Biologic assemblage depends upon the age and the position of the dredged material within the bay. The disposal areas supply large amounts of sediments to the bay and estuary system and expose the poorly consolidated sediments to the action of storm waves. The suspension of these fine sediments results in turbid conditions which affect the photosynthetic activity and the dissolved oxygen content.

Characteristic of many of the deeper bays and water masses, the Houston Ship Channel in Galveston Bay is bordered by subaqueous dredged material.

Coastal Barriers

The barrier islands which parallel the Texas Coastline are highly permeable land bodies separated from mainland bay lagoons and estuaries.

The elevation ranges from sea level to fifty feet (15.24 m) and the island width is from one-half mile to three miles (0.8 to 4.83 km).

VIA. Beach and Shoreface

Beach and shoreface is an area along the gulf side of barrier islands where high wave energy and current activity exists. The shoreface extends from low tide to a depth of 30 feet (9.14 m). The lower shoreface is an area of abundant biological activity characterized by burrowing animals such as crustaceans, molluscs, worms and echinoderms. The upper shoreface is an area of active sediment transport. The beach extends from low tide up to the vegetation line and is characterized by clean, highly permeable sand and shell. The upper beaches supply sand for the maintenance of fore-island dunes.

Almost the entire coast exhibits some type of coastal barrier and all these islands are characterized by beach and shoreface on the gulf side.

VIB. Fore-Island Dunes and Vegetated Barrier Flats

These areas are grass-covered, stabilized dunes and sand flats between the beach and bay-side marshes that cover most of the barrier islands. Vegetation consists of salt-tolerant grasses, rare mesquite, and live oak trees.

These areas occur on all the barrier islands above the Laguna Madre and intermittently from Corpus Christi to Port Isabel.

VIC. Active Dunes

Active Dunes are areas of actively moving sand resulting from the loss of vegetation on fore-island dunes. The sand eventually migrates into the bay and lagoon areas. These areas are most common on Padre Island where the low rainfall and persistent wind are a deterrent to vegetation. Dunes are aligned with prevailing south-easterly winds and are composed of highly permeable sands.

VID. Washovers

Washovers are areas on barrier islands ¼ to 3 miles (0.4 to 4.83 km) wide which channel hurricane storm tides across the islands into bay areas. A large number of the washovers occupy abandoned tidal channels.

Others are the result of poorly developed fore-island dunes. The washovers are areas of intense current activity and scour off large volumes of sand.

Table 3. Summary of Land Use Capability Units

Land Use Capability Unit		Length /a (Miles)	Length (Percentage)
Bays, Lagoons and Estuaries			
IA	River-Influenced Bay	13	1.55
IB	Enclosed Bay	63	7.50
IC	Reef and Reef-Related Areas	12	1.43
ID	Grassflats	117	13.93
IE	Tidal Inlet and Tidal Delta	12	1.43
IF	Open Bay	113	13.45
IG	Enclosed Hypersaline Bay	51	6.07
IH	Sandflats	52	6.19
IJ	Bay or Lagoon Margin	32	3.78
IK	Subaqueous Sandflats	3	0.36
IL	Restricted Hypersaline Bay or Lagoon Margin	12	1.43
IM	Restricted Bay Center	--	0.00
IN	Fresh to Brackish Water Bodies	7	0.83
River Systems			
IIA	Fluvial Woodlands	12	1.43
IIB	Fluvial Brushlands	--	0.00
Coastal Wetlands			
IIIA	Saltwater Marsh	89	10.59
IIIB	Brackish to Freshwater Marsh	140	16.67
IIIC	Brackish-Water Marsh	8	0.95
Coastal Plains			
IVA	Prairie Grassland	71	8.45
IVB	Loose Sand and Loess Prairies	--	0.00
IVC	Intense Wind Deflation	--	0.00
IVD	Saline Grasslands	26	3.10
Made Land and Disposed Dredge Material			
VA	Made Land	9 /b	--
VB	Subaerial Disposed Dredged Material	235 /b	--
VC	Subaqueous Disposed Dredged Material	90 /b	--
Coastal Barriers			
VIA	Beach and Shoreface	--	0.00
VIB	Fore-Island Dunes and Vegetated Barrier Flats	7	0.83
VIC	Active Dunes	--	0.00
VID	Washovers	--	0.00
	TOTAL	840	100.00

/a Length which the canal or dredged material passes through or is adjacent to the land use capability unit.

/b Not included in total.

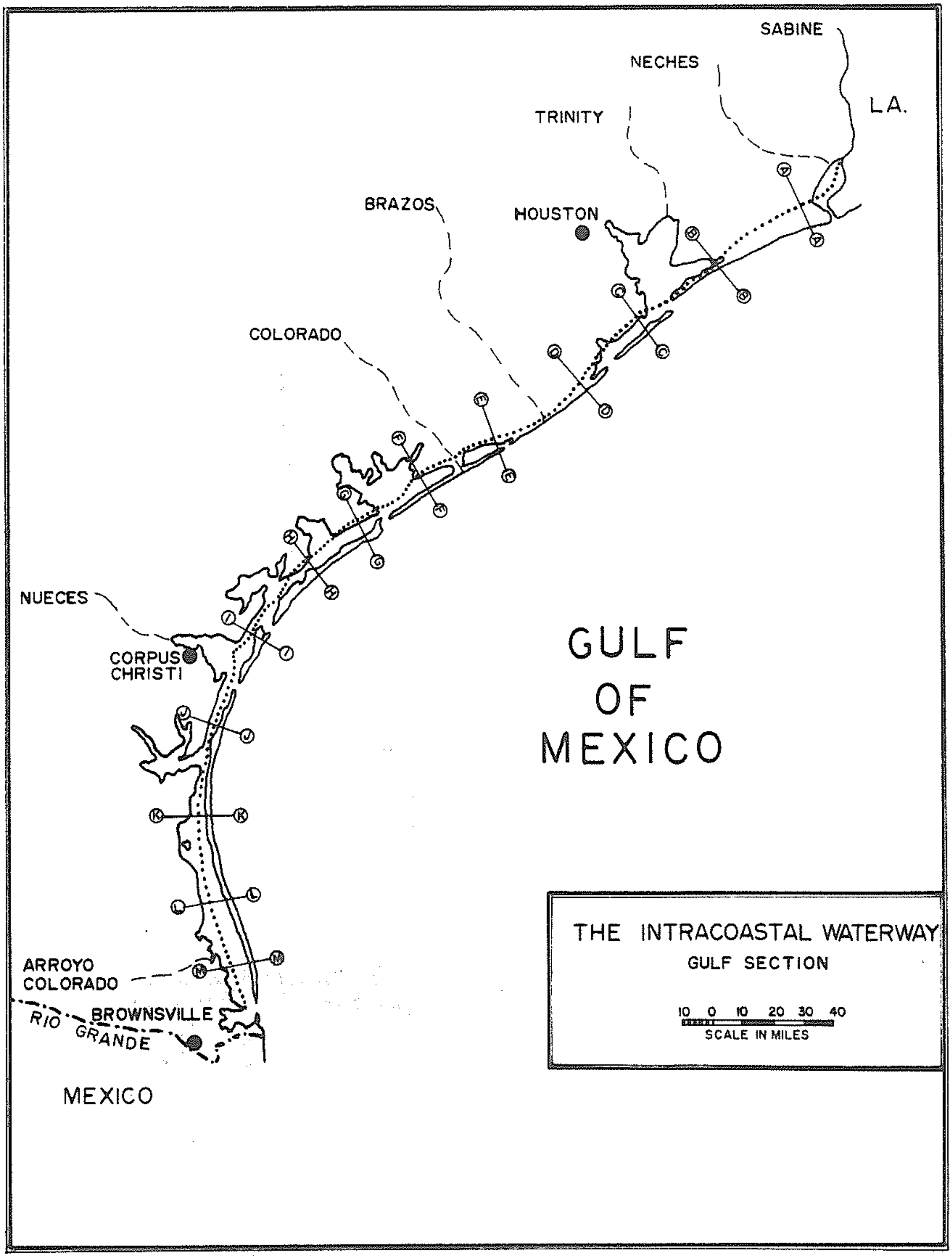

Figure 6. Location of Land Use Capability Unit Maps

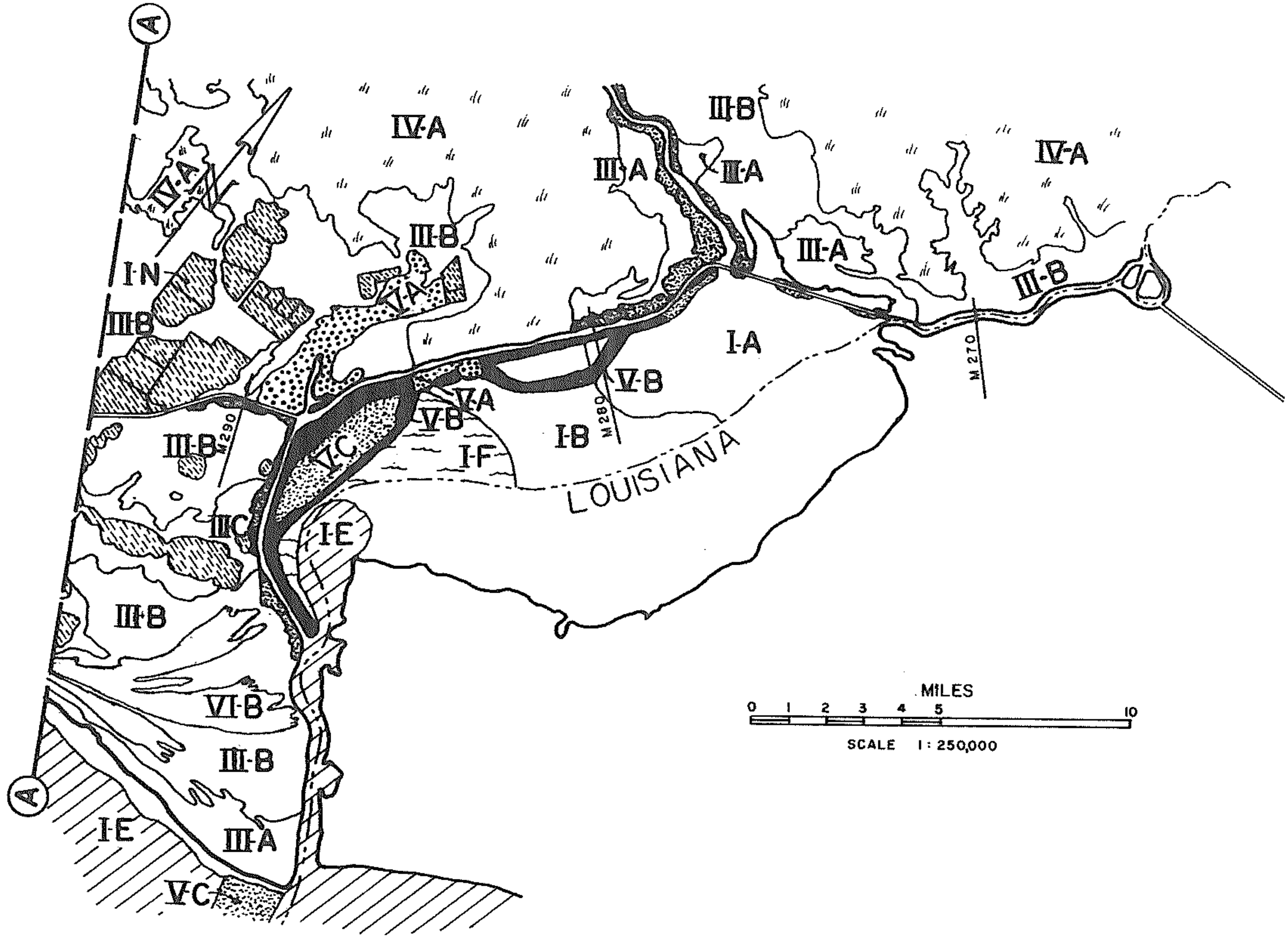

Figure 7A. Land Use Capability Units near Sabine Lake

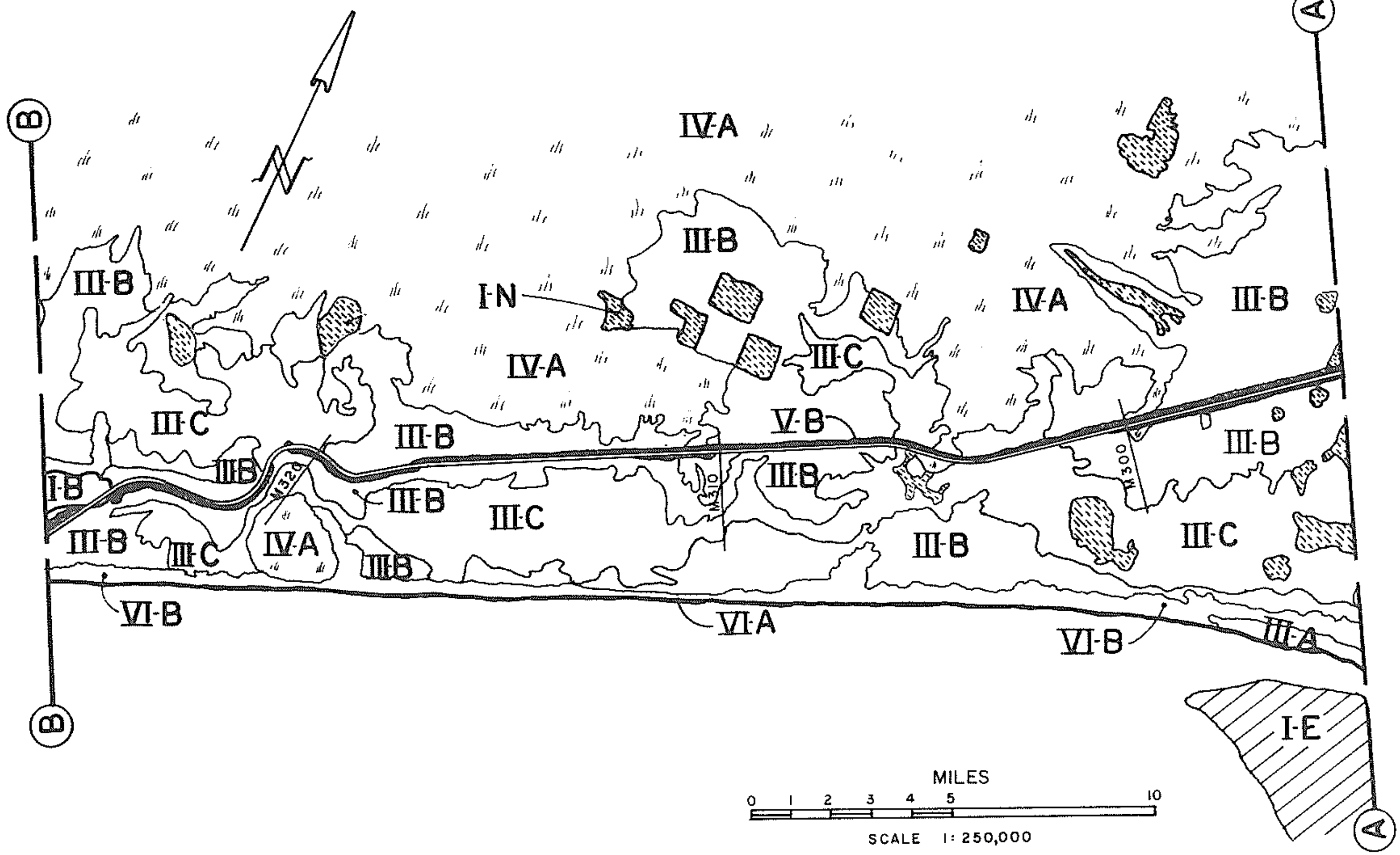

Figure 7B. Land Use Capability Units Sabine-Galveston Area

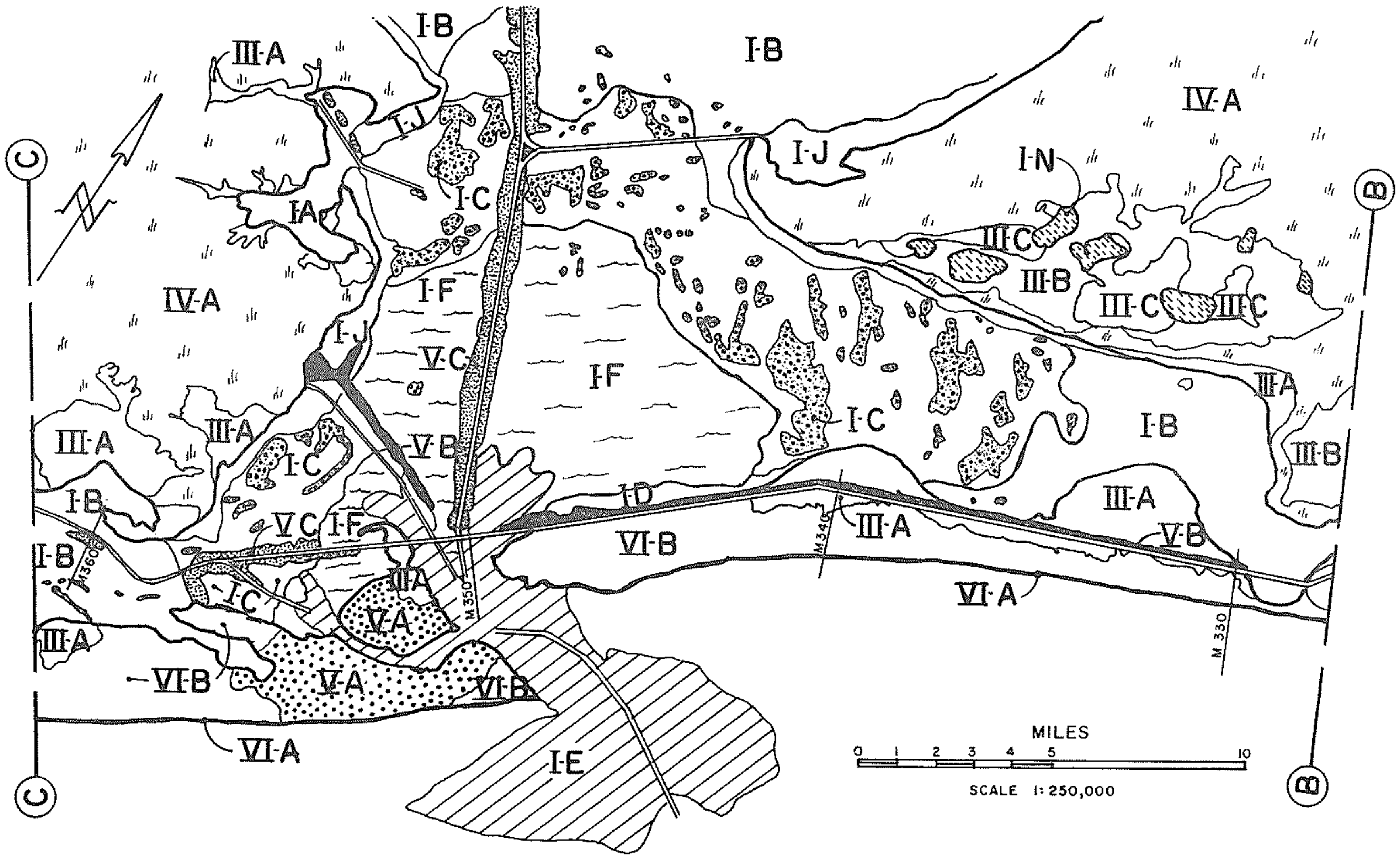

Figure 7C. Land Use Capability Units for Galveston Bay

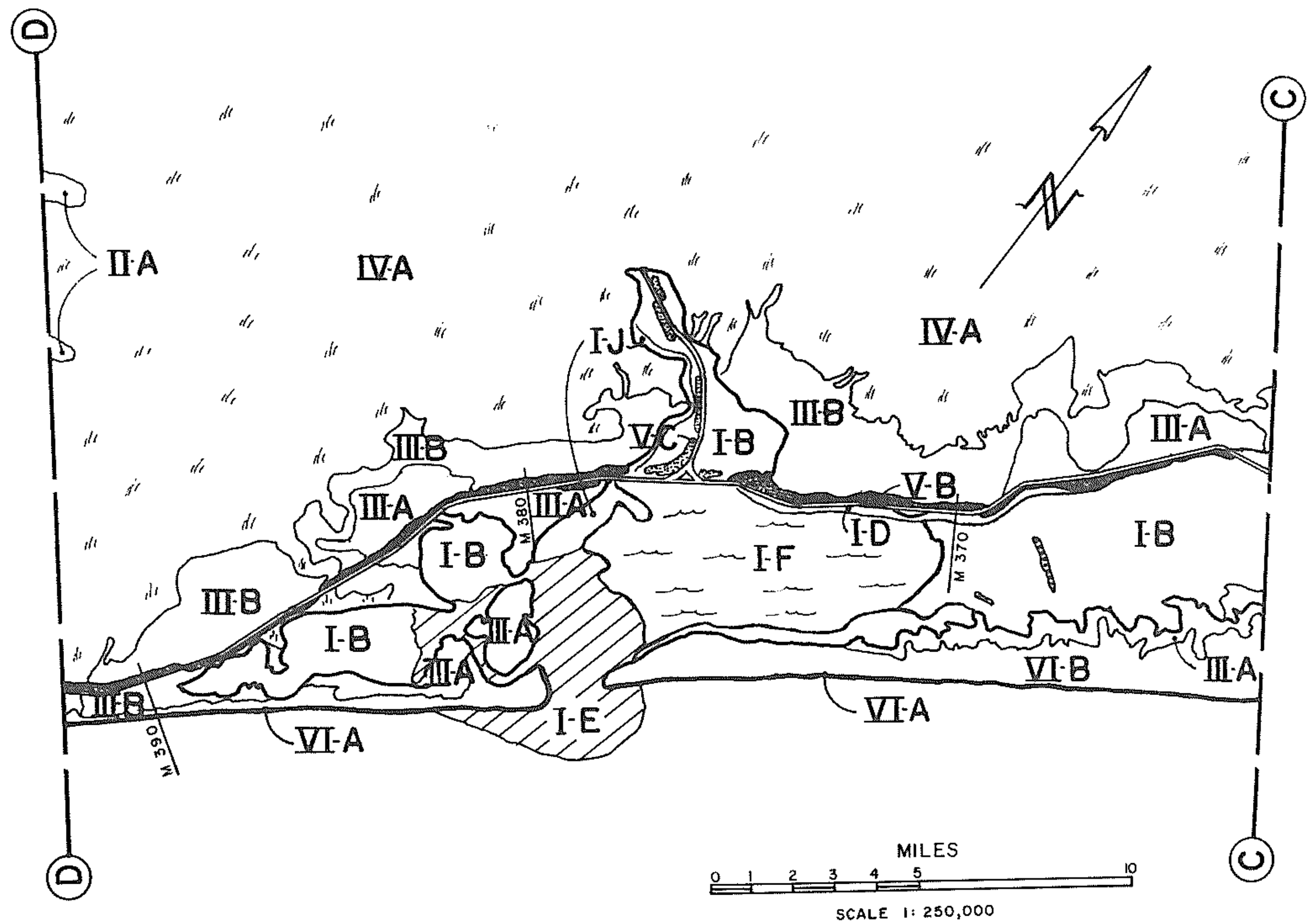

Figure 7D. Land Use Capability Units for West Bay

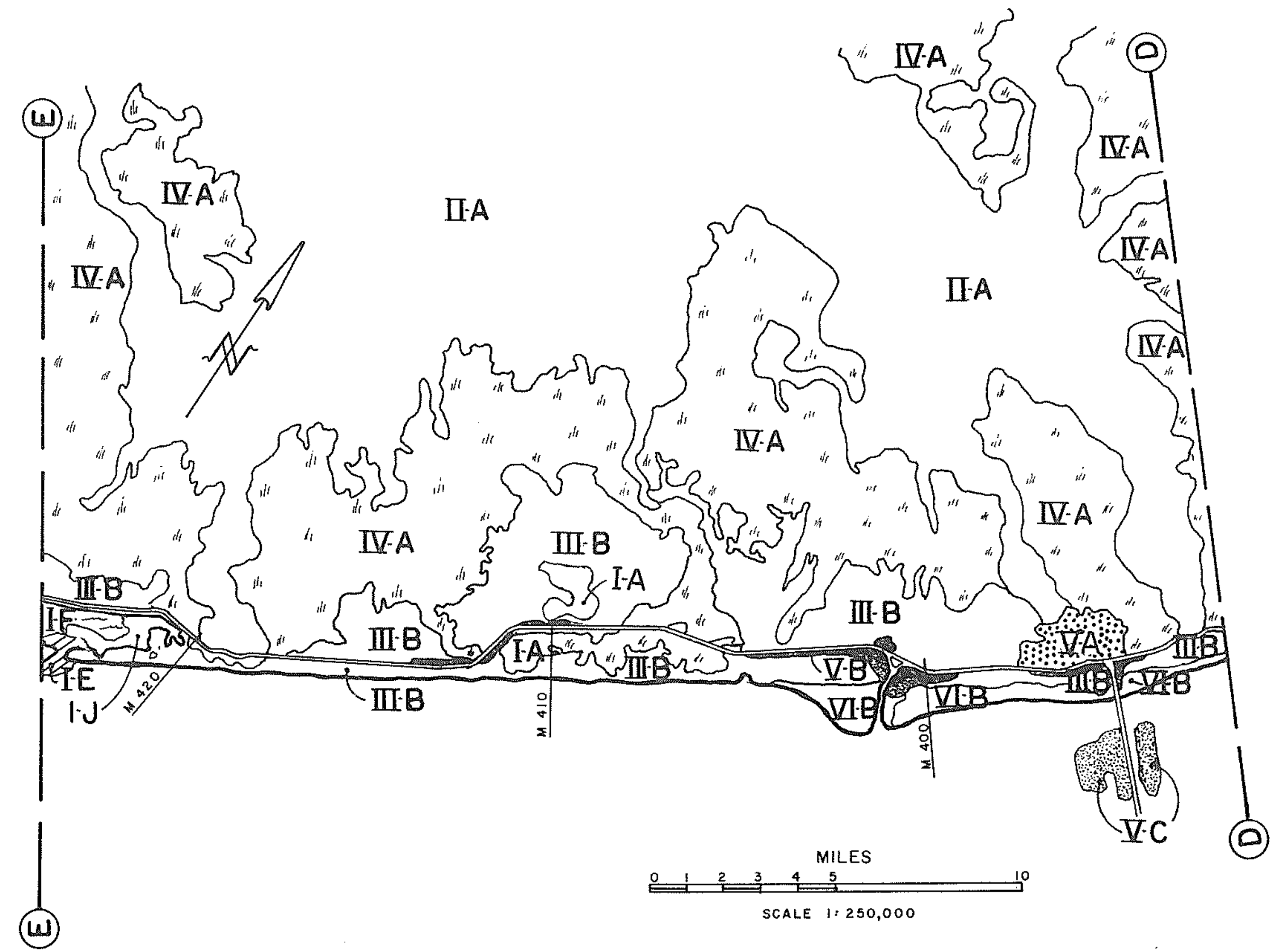

Figure 7E. Land Use Capability Units Near Freeport

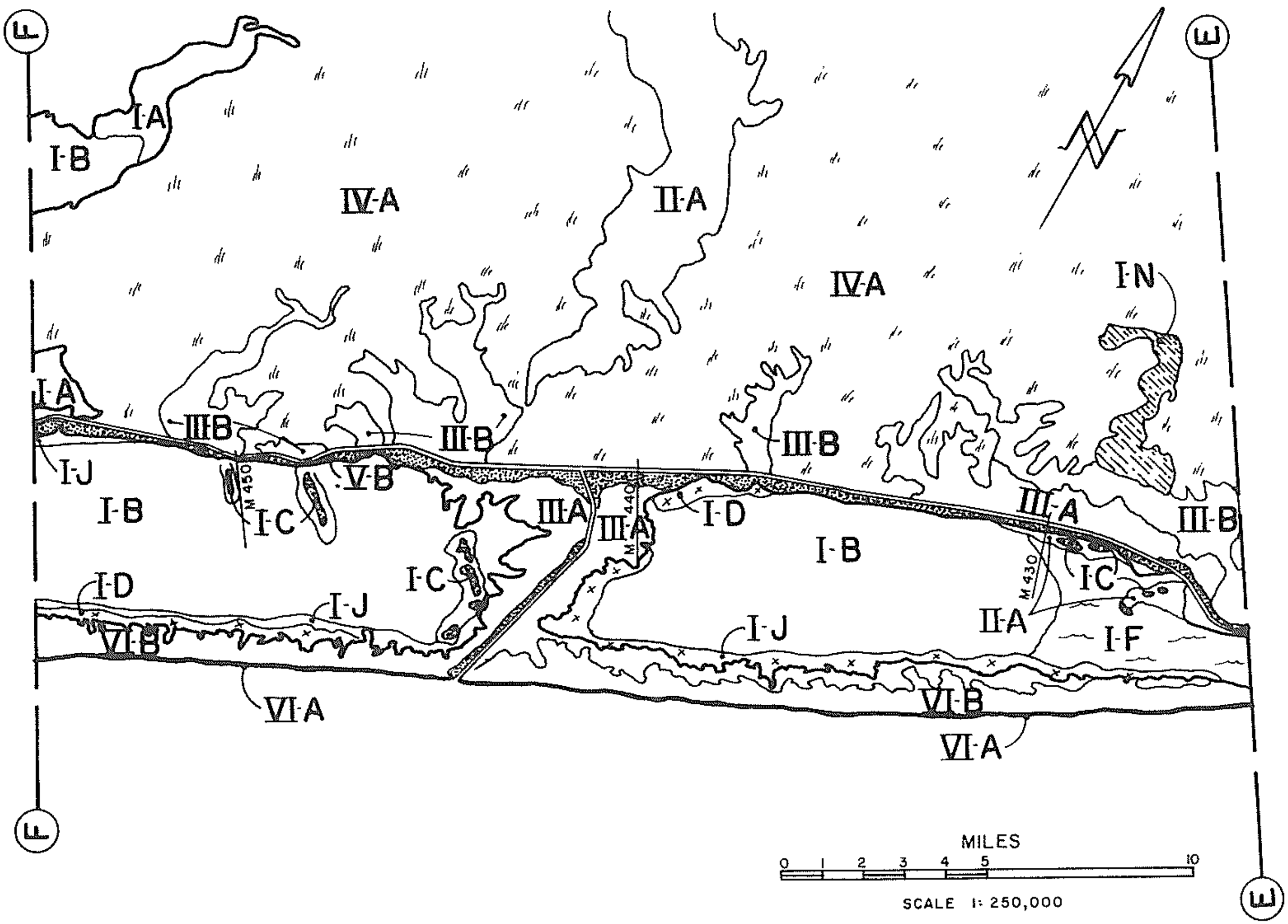

Figure 7F. Land Use Capability Units Near Colorado River

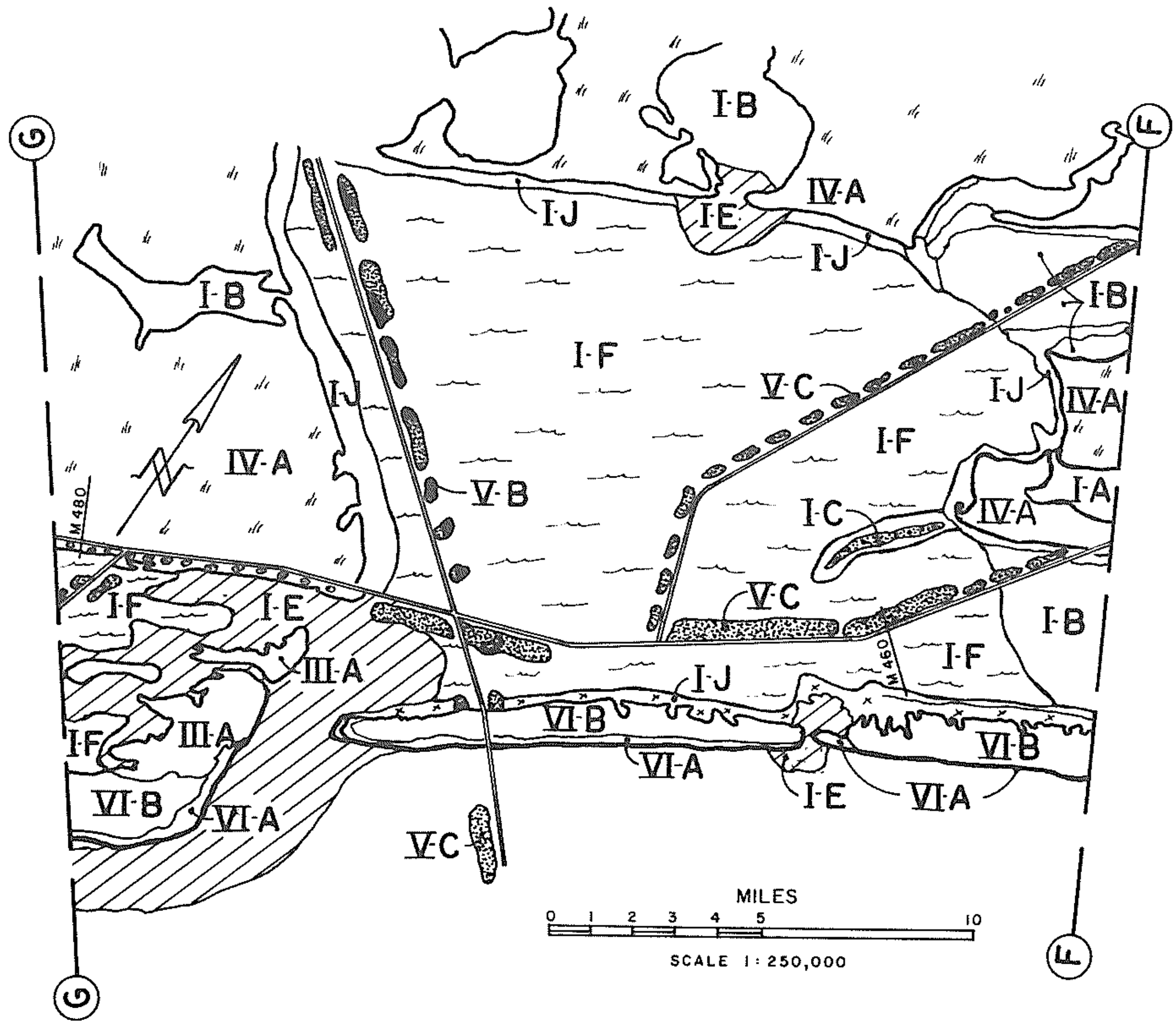

Figure 7G. Land Use Capability Units for Madagorda Bay

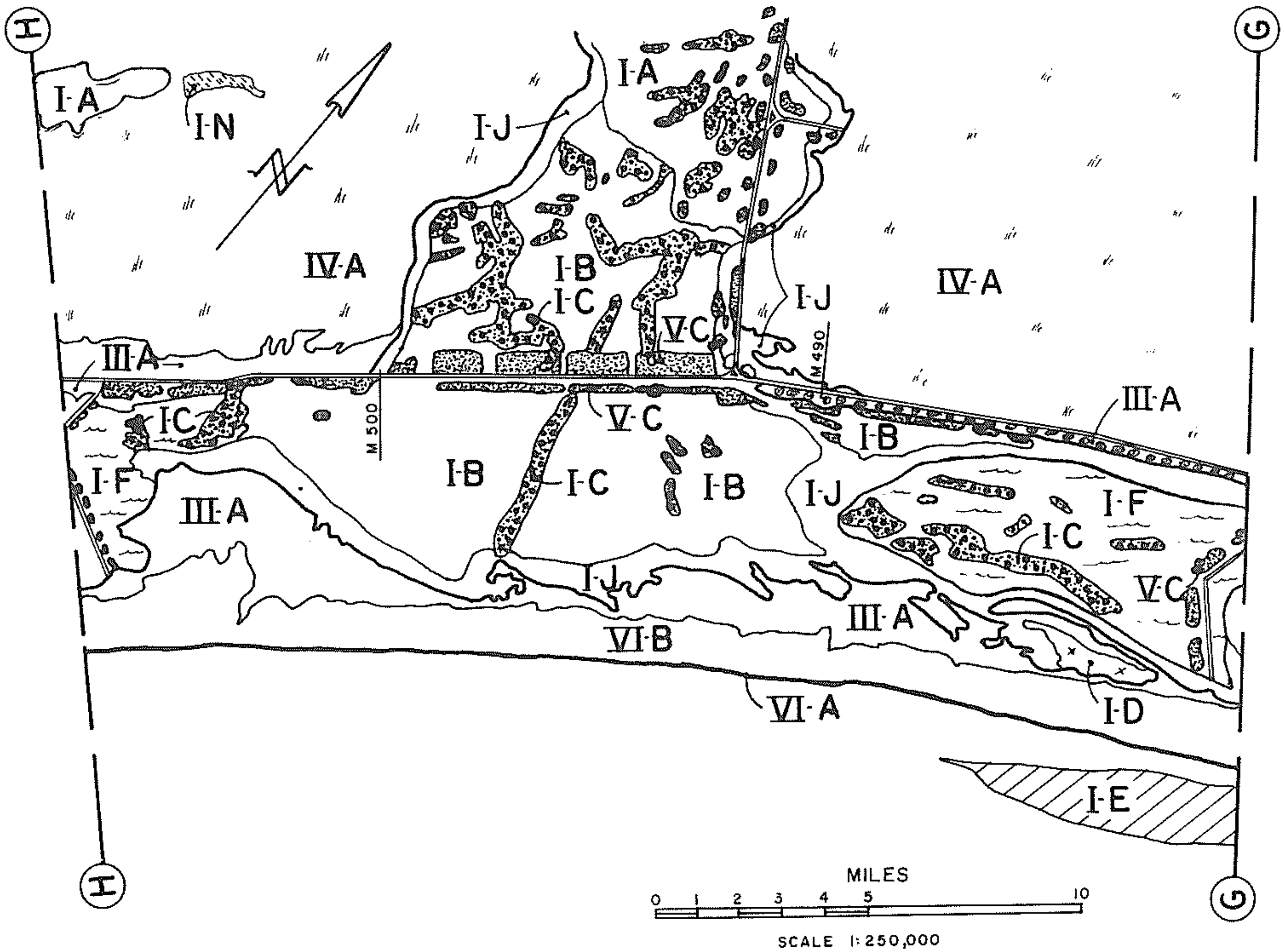

Figure 7H. Land Use Capability Units Near San Antonio Bay

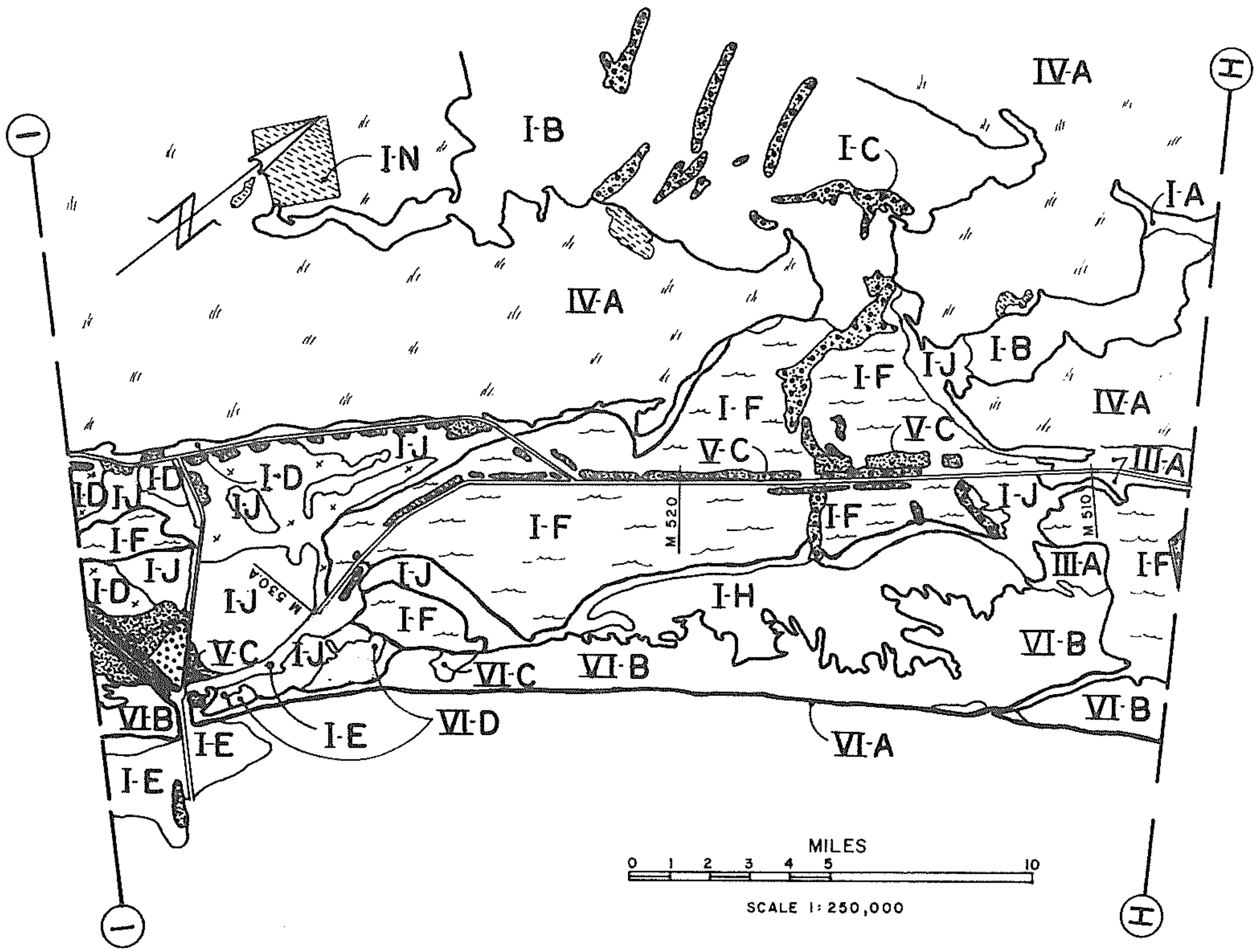

Figure 7I. Land Use Capability Units Near Aransas Bay

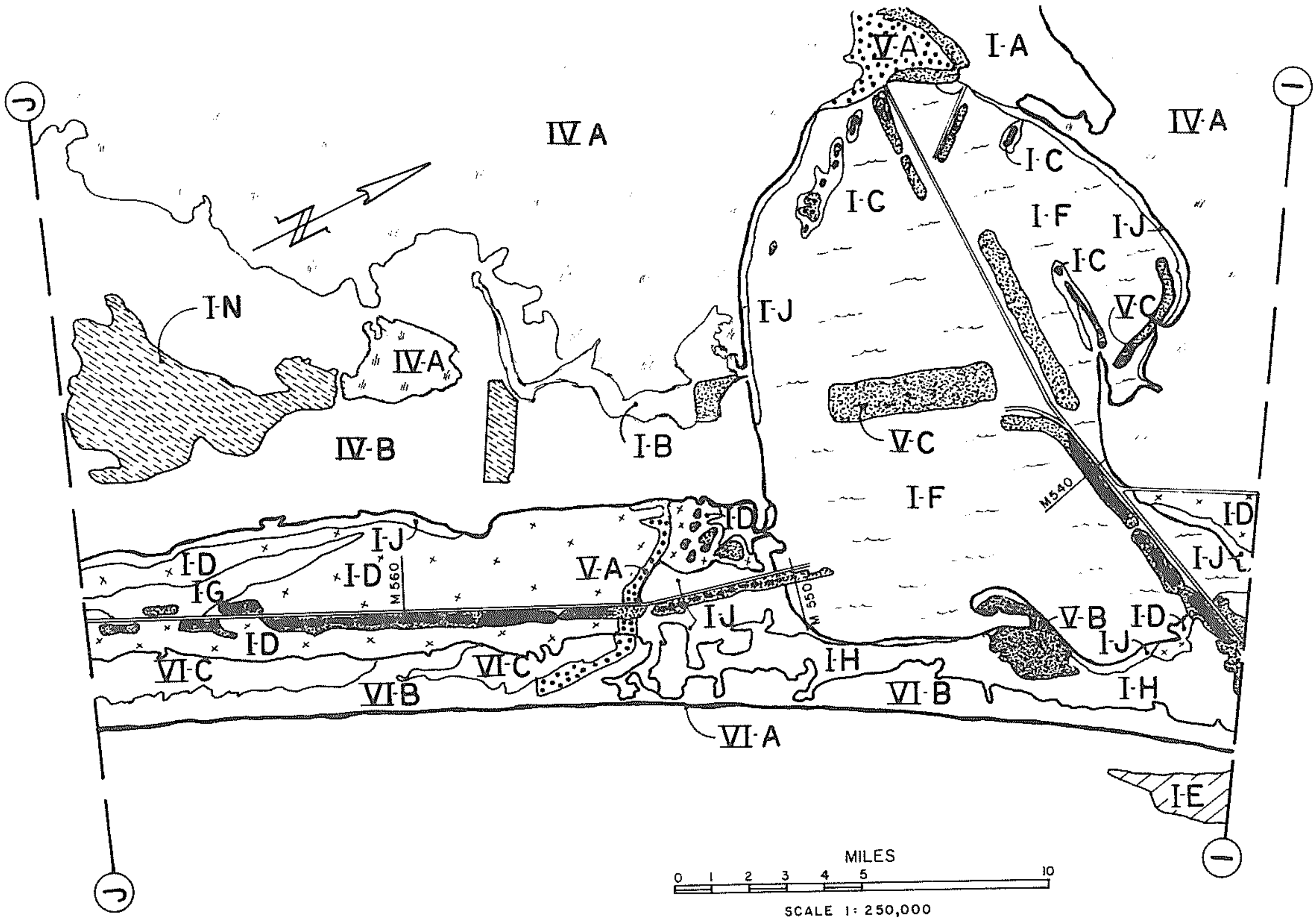

Figure 7J. Land Use Capability Units Near Corpus Christi

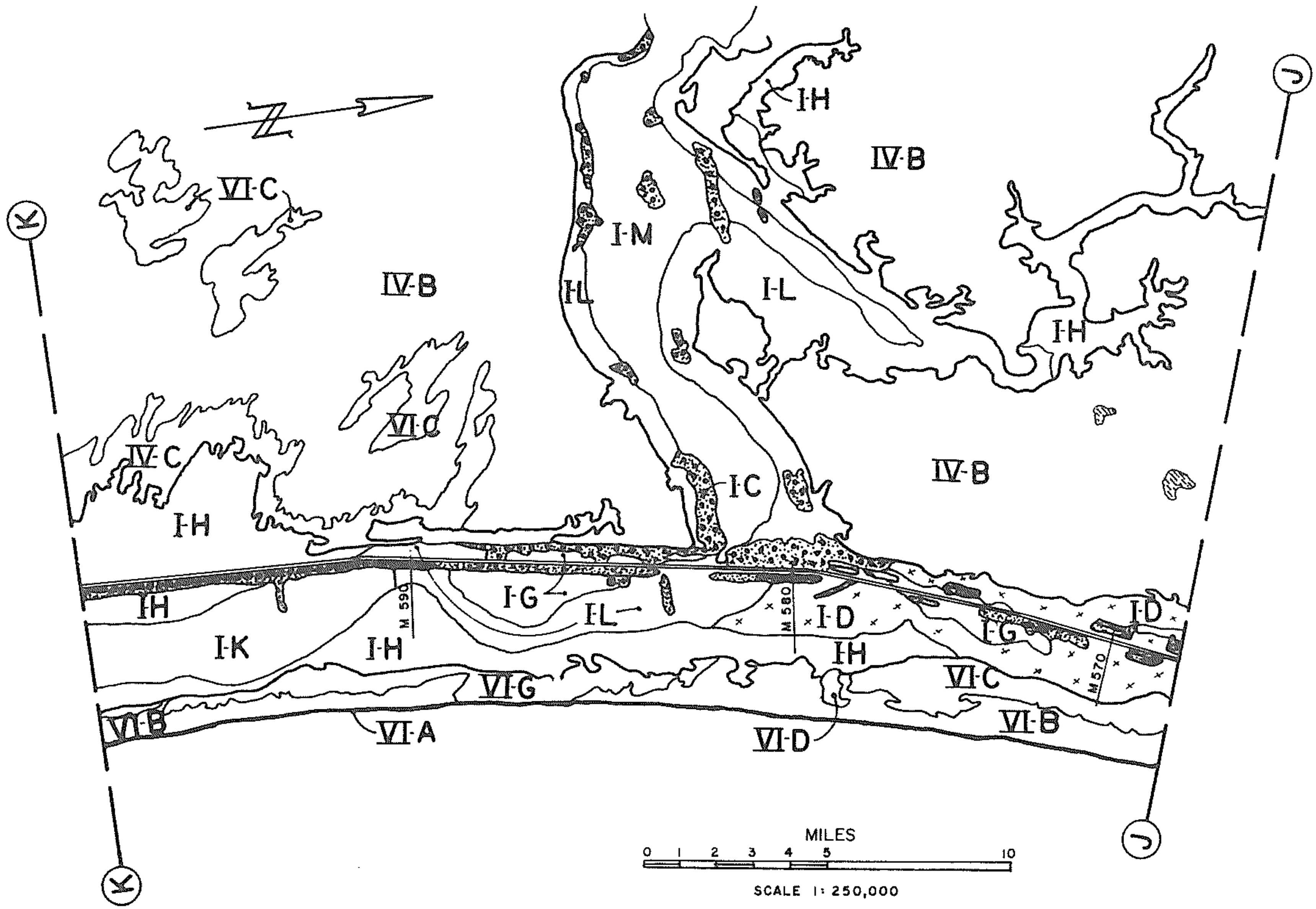

Figure 7K. Land Use Capability Units Near Baffin Bay

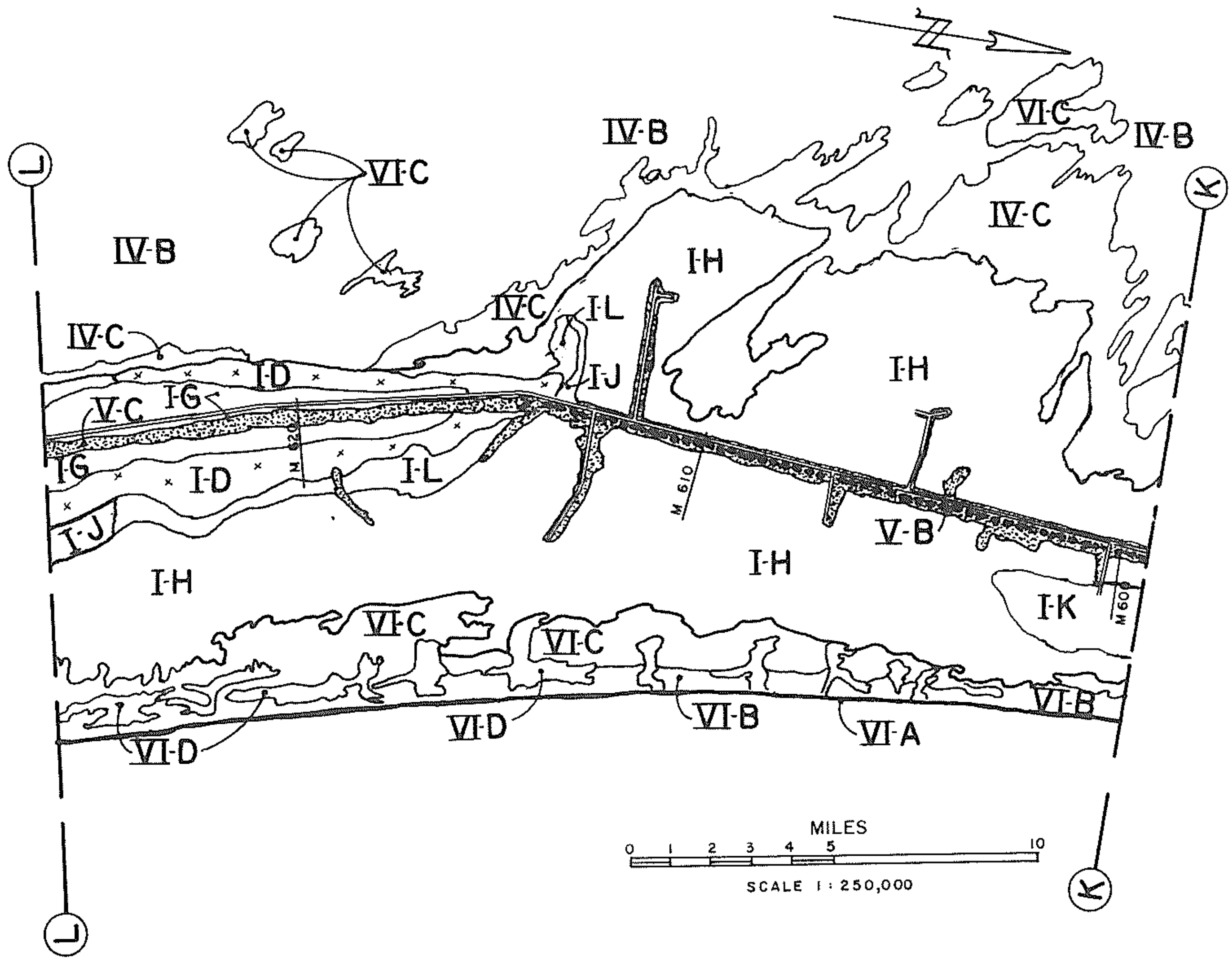

Figure 7L. Land Use Capability Units Near the Land Cut

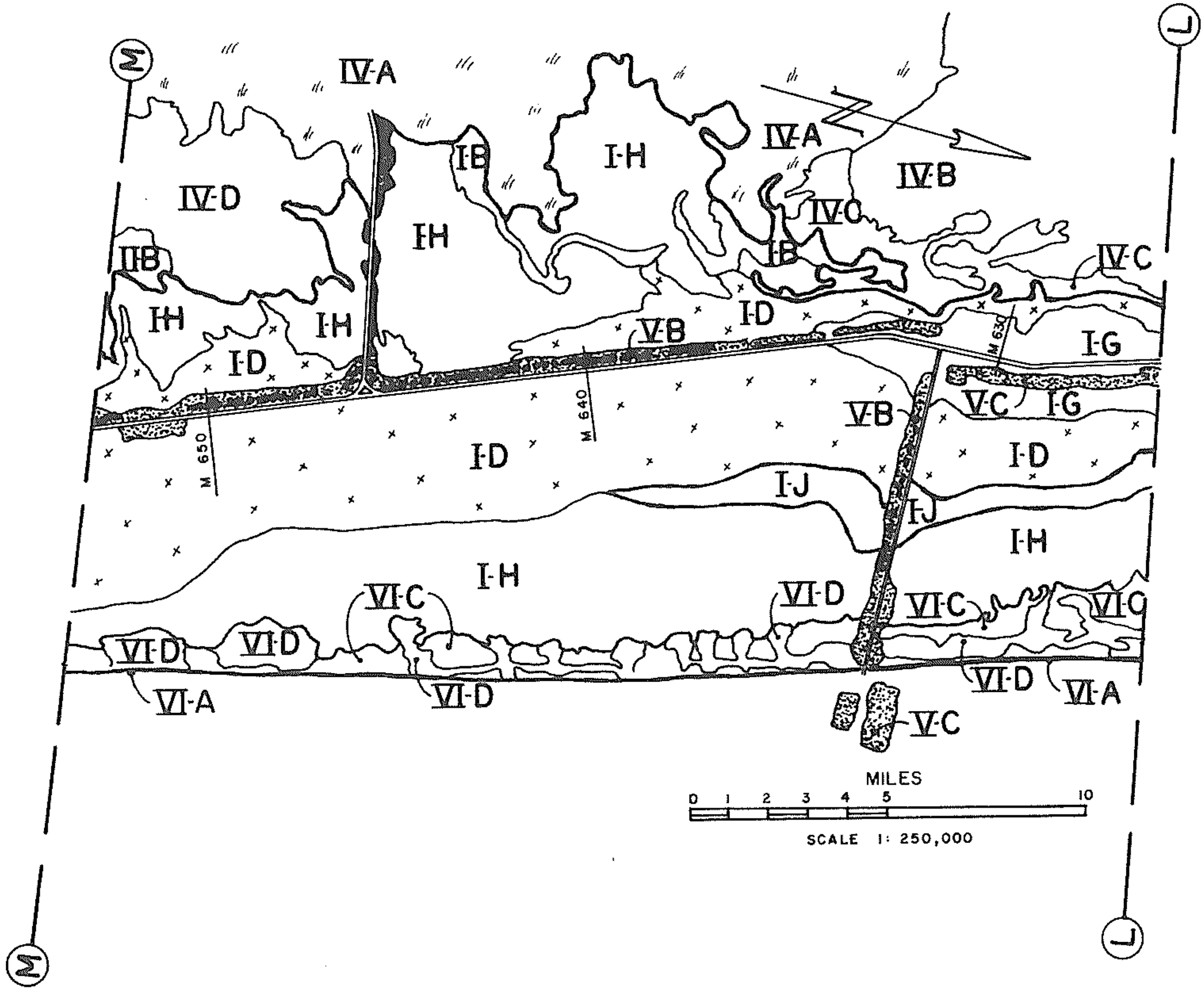

Figure 7M. Land Use Capability Units Lower Lagoon Madre

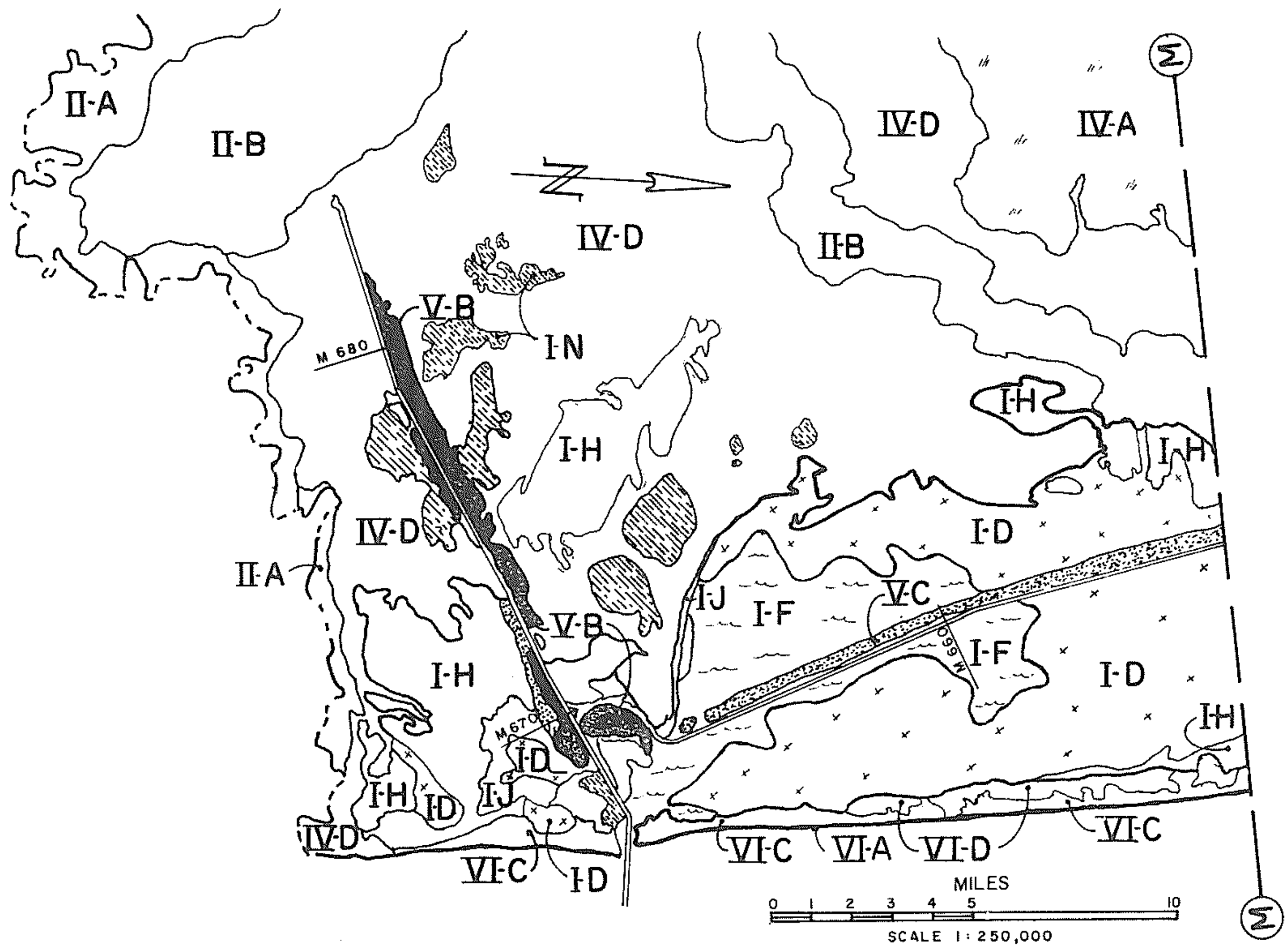

Figure 7N. Land Use Capability Units Near Brownsville

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CHAPTER III

WATER AND SEDIMENT QUALITY

Field Sampling

The sampling program along the Gulf Intracoastal Waterway (GIWW) was established in order to ascertain background water and sediment quality. Sampling stations along the GIWW were selected at approximately six-mile (11 km) intervals. Wherever the canal intersected a river, additional stations were added. A literature review of environmental quality along the canal was conducted and past problem areas that had been identified were also sampled.

The field sampling programs were conducted along the total length of the waterway in January 1975 and August 1975 from the research vessel RV/EXCELLENCE. An outboard motor boat was used for sampling selected areas of the waterway in May 1975. The RV/EXCELLENCE was equipped with water quality monitors to measure water temperature, dissolved oxygen, salinity, pH, Eh, and turbidity. The following sampling procedures were employed.

a. Water depth in feet was determined by a fathometer aboard the sampling vessel.

b. Water salinity was measured by an electronic salinity meter, which had been calibrated against known salinity standards.

c. The dissolved oxygen in mg/l was read directly from an oxygen meter. The meter was calibrated using the air calibration technique, as well as standard oxygen titration procedures.

d. Water temperatures were measured electronically with a mercury thermometer used as a standard.

e. pH measurements were made with a pH meter calibrated by standard buffer solutions.

f. Water and sediment Eh (oxidation-reduction potential) were determined using a Corning Digital 110 pH-Eh meter. The Eh measurements were made using platinum and standard calomel electrodes.

g. Turbidity was determined using a Hach turbidity meter. The instrument was calibrated against a standard solution of 100 Formazin turbidity units (FTU).

h. Water samples were obtained for laboratory analysis of total organic carbon. The samples were purged and sealed when collected in glass ampules after the addition of potassium persulfate and phosphoric acid as a preservative.

i. Samples for later water quality analysis were obtained from a mid-depth level by the use of a metal free Kemmerer water sampler. A one-liter cubitainer was filled approximately 3/4 full, marked with the station number, date, and N for nutrient. The sample was then placed in the freezer aboard the vessel and it remained frozen until subsequent analysis for solids and nutrients. A second one-liter sample was obtained for metal analysis and marked with an M for metal.

j. Sediment samples were obtained using either an Ekman Dredge, or Phleger gravity corer. The corer was equipped with a four-foot (1.22-m) barrel. The barrel was lined with a cleaned 1.5-inch (3.8-cm) diameter plastic core tube. After sample collection, the plastic tube was removed from the core barrel and sealed at each end with polyethylene film and cork. The samples were immediately frozen and later transported to the Texas A&M campus where they remained frozen until time for analysis. When cores could not be obtained, a grab sample was taken for chemical analysis by an Ekman Dredge with care not to introduce metal contamination into the sample. The sediment was then placed in a clean one-quart plastic freezer container, or Nasco Whirl-Pak Plastic bag, labeled and frozen.

k. Sediment Eh was determined immediately at each station. This was necessary since the Eh of the sediment is subject to rapid change when exposed to air. The sample was analyzed in the same manner as water Eh using the Corning Digital 110 pH-Eh meter. Sediment pH was analyzed immediately by immersing the pH electrodes into the sediment and recording the meter value.

Water Quality Analysis

The water quality parameters determined in the laboratory included total suspended solids, total organic carbon, selected heavy metals, and the nutrients including ammonia, nitrate and nitrite nitrogen and phosphate phosphorus. All analyses were carried out using analytical methods described in the APHA publication "Standard Methods for the Examination of Water and Wastewater," 13th Edition, 1971 or the EPA Manual, "Methods for Chemical Analysis of Water and Wastes," 1974. The procedures are briefly described in this section.

a. Suspended and volatile solids were determined gravimetrically as per APHA Standard Methods.

b. Samples for total organic carbon were preserved and determined utilizing the ampule method of the Oceanography International Carbon Analyzer System.

c. Heavy metal analyses of the water for Cadmium (Cd), Copper (Cu), Lead (Pb), Mercury (Hg), and Zinc (Zn) concentrations were conducted. After the samples were adjusted to pH 3, ammonium pyrrolidine dithiocarbamate was added, and the metals were extracted in 4-methyl

2-Pentanone (M.I.B.K.), and analyzed on a Perkin-Elmer Model 303 or 403 Atomic Absorption Spectrophotometer.

d. Nutrient analysis consisted of the evaluation of ammonia-nitrogen (NH_3-N), nitrite-nitrogen (NO_2-N), nitrate-nitrogen (NO_3-N), and phosphate-phosphorus (PO_4-P).

e. Ammonia nitrogen was measured by a colorimetric modification of the Nesslerization method as per Standard Methods for the January samples. Samples obtained at other times were analyzed according to the Selective Ion Electrode Method, EPA 1974, in order to expedite analysis time.

f. Nitrite and nitrate nitrogen concentrations were determined by using an automated colorimetric system (Technicon Auto-Analyzer II system). This EPA approved method determines NO_2-N by the conventional diazotization-coupling reaction. The NO_3-N is reduced with hydrazine sulfate and the nitrite thus formed is determined in the above manner. Subtraction of the NO_2-N originally present in the sample from the total NO_2-N found, gave the original NO_3-N concentration in terms of NO_2-N.

g. Phosphate phosphorus was analyzed as orthophosphate by the Ascorbic Acid Method for the samples obtained in January and August. For the samples obtained in May, a persulfate digestion was first employed to express the data as total phosphate phosphorus.

Sediment Analysis

Sediment samples were obtained at all but three stations on the January cruise. These three stations have a bottom consisting of either hard clay, fine sand, or shell which the samplers could not penetrate. At the time of analysis, the frozen cores were removed from the plastic core tubes, and split into fractions by depth and sediment type. For the majority of stations the top 3.9 inches (10 cm) was thoroughly mixed and analyzed according to the EPA guide "Chemistry Laboratory's Manual, Bottom Sediments," 1969, as compiled for the Great Lakes Region.

a. The Five-Day Biochemical Oxygen Demand test for sediments was conducted by blending weighed amounts of sediments in biologically seeded saline water. A YSI Model 51A Oxygen Meter was then used to determine the dissolved oxygen values.

b. The percent of total volatile sediment solids was determined in accordance with EPA procedures (1969).

c. Metals analysis of the sediment for cadmium, copper, lead, and zinc followed the EPA procedure. Briefly, this consisted of leaching the metals from the sediments by digestion with concentrated nitric acid and 30 percent hydrogen peroxide, concentrating by evaporation and placing in a 10 percent acid solution. The metals analysis was performed on a model 303 or 403 Perkin-Elmer atomic absorption spectrophotometer in accordance with the manufacturer's recommended procedures.

Previous Studies Along Gulf Intracoastal Waterway

The following reports have been published and serve as an available reference of past data collected for sections of the Gulf Intracoastal Waterway.

a. Maintenance Dredging GIWW by Army Corps of Engineers. From Nov. 1971 to July 1973, physical and chemical data were obtained for water and sediment along the Gulf Intracoastal Waterway near dredged material disposal sites (U.S. Army Corps of Engineers, 1975).

b. Galveston Bay Project-Compilation of Water Quality Data from July 1968 to Sept. 1971 by Tracor Inc., Austin, Texas. Physical, chemical and bacterial data were obtained for selected stations in Galveston Bay (Huston, 1971 and 1973).

c. Seadock Offshore Supertanker Port Facility. Report prepared for Seadock Inc. Houston, Texas in part by Civil Engineering Department, Texas A&M University. Physical, chemical and sedimentary data were obtained in the area offshore from Freeport, Texas, as well as from rivers and the Intracoastal Waterway in this same general area.

d. Water Quality Management in the Brazos River Coastal Zone by R.E. Withers and R.L. Garrett (1975). During 1974, physical, chemical and sedimentary data were obtained in the Brazos River, GIWW, and other waterways in the Freeport, Texas area by the Civil Engineering Department, Texas A&M University.

e. Sediment Analysis Galveston Bay by R.W. Hann and J.F. Slowey (1972). From December 1971 to July 1972 sediment data regarding heavy metals, oxygen demand and pesticides were measured by the Civil Engineering Department, Texas A&M University.

f. Natural Background Levels of Heavy Metals in Texas Estuarine Sediments by J.F. Slowey, et al. (1973). Sabine Lake, Galveston Bay Area and Corpus Christi Bay Area were sampled from January 1972 to July 1973 by the Civil Engineering Department, Texas A&M University.

g. Field and Analytical Studies of the Corpus Christi Ship Channel and Contiguous Waters by R.E. Withers, et al. (1973). From September 1971 and 1973 heavy metal determinations were conducted to demonstrate the use of an analytical model by the Civil Engineering Department, Texas A&M University.

h. Field Studies in the Brownsville Ship Channel and GIWW by R.E. Withers, R.L. Garrett and R. Maldonado (1975). Physical and chemical data were obtained for water and sediment by the Civil Engineering Department, Texas A&M University.

Results

Graphical representations of the water and sediment quality data are presented in the following pages. All of the parameters which displayed a significant variation in concentration were plotted. The water and sediment quality data are listed in tables in the Appendix. Several of the parameters exhibit seasonal fluctuations which could be attributed to flooding conditions encountered while sampling in January and May.

In the following figures, points connected by a solid line represent the January data, while a dashed line denotes the August data. Individual points marked with an X were recorded in May. Points that are denoted with a solid circle represent values obtained by other agencies at various times of the year in that location. Sample values obtained in rivers upstream from the GIWW are not included in these figures. The data for some of the parameters were for surface water while others were from a middepth location. Mileages obtained from the figures may easily be correlated with their approximate location by use of Table 4.

Discussion

Data obtained for some of the parameters in this study remained fairly constant along the GIWW. These included the percent saturation of dissolved oxygen and temperature which were affected by seasonal fluctuations. Changes in pH were generally associated with salinity variations.

Reach One - Orange to Galveston Bay

Reach One includes the area from Sabine River to Galveston, a distance of ninety miles (mile 266 to 356). The region is primarily wet subtropical with an average rainfall of 38 to 50 inches (965.2 to 1270 mm) per year. This large rainfall and subsequent high river inflows into the bay systems produce low salinities in much of this reach. Galveston Bay and Sabine Lake are the major bodies of water in the reach with the GIWW acting as a connecting link between them.

When reviewing the data for this reach the parameter with the largest variation was the salinity. The Texas GIWW begins in the Sabine River near Orange and continues toward the coast along the west side of Sabine Lake. At a point near Port Arthur the GIWW leaves the lake and proceeds toward Galveston Bay in a channel that is almost completely man-made. The salinity remained near that of fresh water until East Galveston Bay was approached about mile 332, Figure 8.

These data indicate that freshwater flows from Sabine Lake into Galveston Bay are very significant since chemical pollutants in the waters of the Sabine River or Lake could be transported directly to Galveston Bay via the GIWW. Due to the high concentration of industry in the Beaumont-Port Arthur-Orange area, as well as the associated high level of shipping in the reach, the probability of an accidental chemical discharge into the water is ever-present. Depending on the substance, concentration, and location, the environmental effects could be severe.

One highly visible example of this problem is the advance of water hyacinth from the area of Sabine Lake down the GIWW. This situation was first noticed on the August 1975 cruise. The water hyacinth was rapidly multiplying in secluded portions of this reach along the canal shoreline.

In at least one instance, this plant had almost extended across the entire width of the canal. The hyacinth is being spread by the natural currents as well as barge traffic. A herbicide similar to those used on lakes may be required to deal with this problem.

Changes in water salinity are accompanied by changes in pH and Eh, Figures 11 and 12. The pH values of the water ranged from 7.4 in the freshwater section to 8.4 in the bay. Variations in these parameters can be observed as a steady increase closely following the salinity gradient.

Turbidity values, Figure 13, for this reach maintain a higher level than those found in any of the other sections. In January, this was due to the large volume of sediment-laden river water entering the reach. The predominately silty-clay type soil found in the upper part of this reach can easily become suspended in the water. None of the values, however, should present any severe problems to aquatic organisms.

The highest phosphate values obtained in the study were recorded in the area where the Houston Ship Channel intersects the GIWW, Figure 14. Phosphate values obtained in this area correlate well with previous data. The data seem to indicate a seasonal trend whereby the phosphate level rises in the fall or winter and declines in the summer months. One possible explanation for the values is that large amounts of phosphate probably enter the bay from the numerous industrial and urban sources. One effect of this seasonally produced phosphate-rich water could be an increase in the number of photosynthetic planktonic organisms in the area. If the dissolved oxygen percent saturation values are observed in Figure 9, the values rise in this area on each of the three trips.

Ammonia, nitrate, and TOC values in this reach were generally greater than the values obtained in the other reaches, Figures 15, 16, and 19. The probable reason is the high industrial and municipal concentrations in this reach. Several locations were observed where urban runoff directly enters the canal. Nitrite nitrogen values were also observed to rise in a part of the reach called Oil Well Slough.

The solids concentration in the water was lower in the August trip than in either of the other trips, Figures 17 and 18. In May much rain and flooding was encountered, with January also being a fairly wet month. For most locations the volatile solids were between 10-15 percent of the total solids concentration indicating no excessive organic loadings.

When dissolved metals in the water were analyzed in this reach, Figures 20, 21, and 22, none were above the recommended EPA guidelines values for a marine or freshwater system. A very interesting plot was obtained for lead in the January data. Many scattered peaks were obtained at this time for lead only in reach one and the first part of reach two. Therefore, a strong correlation seems to exist between these peak values and the percent of commercial traffic and urban runoff in these areas.

Zinc values were high in this reach as compared to the rest of the waterway. The many industrial and domestic uses of this metal are probably responsible for these values occurring in the water. None of the stations had a value for zinc greater than the recommended level of 100 ppb. Most of the stations had values much less than this value.

Copper values were high in January and May where the Neches River joins the Sabine. Since these were wet months and many industries are located in this area, water runoff was probably responsible for an increase in copper and lead in this area. All of the stations in the area of the intersection of the Houston Ship Channel and GIWW displayed a rise in dissolved metals values in January and May. This rise is probably attributable to increased runoff into Galveston Bay during this time of the year.

The metals in sediment for reach one correspond fairly well with the metals in water at each location. A cause of some concern is that the cadmium level increases to between 2 and 3 ppm alternately in January and May in the first two stations. Since these sites are near industrial activities, they should be investigated further as to the possible source of the metal.

Data obtained for copper in the sediment of stations located in Galveston Bay agreed well with values obtained by the Civil Engineering Department (Hann and Slowey, 1972). Lead values, however, were somewhat higher in these locations than had been previously published in this same report.

Zinc values in the sediment of this first reach were about the same as observed in the other reaches. No relation can be seen between the values and the water quality or specific industrial sites along the reach.

Reach Two - Galveston Bay to Corpus Christi Bay

The second reach extends from Galveston to Corpus Christi a distance of approximately 182 miles, (mile 356 to mile 538). Climatic conditions in the reach are produced by the semi-arid area to the west and humid region to the northeast, with warm moist winds from the Gulf always present. The average annual rainfall varies from 30 to 38 inches (762 to 965 mm) per year, a decrease of twenty-five percent from the first reach.

This reach has many bays with rivers flowing into them. Corpus Christi, Nueces, Aransas, San Antonio, Espiritu Santo, Matagorda and West Galveston are the main bays in this reach. Corpus Christi and Matagorda Bays are the deepest bays with large sections exceeding 12 feet (3.66 m). Several barrier islands stretch along the coastline and serve as one side of the bays. They are characterized as high, vegetated sand dunes that have been fairly well stabilized in their location.

When analyzing the data obtained for this second reach, the greatest variability is found in the salinity, Figure 8. It follows an expected pattern of rising where Gulf waters come into direct contact with GIWW water, and falling in the area of major river inflows. The January values closely parallel the August data with the only difference being consistently lower salinity values in January due to higher river inflows and less evaporation in the area. Turbidity values for the reach were similarly less in August than January, and were also related to stream flow conditions.

Phosphate values in this reach were found to vary considerably, Figure 14. Many of the peak points correspond with significant water inputs to the bay or directly to the GIWW. The highest values for ammonia nitrogen along reach two were found in the Brazos River area. These are consistent with values previously reported by the Civil Engineering Department, Texas A&M University (Withers and Garrett, 1975). In their studies major sources of ammonia in the Brazos River have been related to the many domestic sewage treatment facilities scattered along its banks. High values for nitrate nitrogen were also recorded in the Brazos River area, and were attributable to the same sources. Another rise in ammonia was also noted in the Caney Creek area (mi. 419) which has several small towns along its upper shores. Elevated nitrate values in the January data were in the area of the Colorado River and the town of Matagorda. As can be seen in Figure 16, an abrupt rise is evident when approaching the river and then slowly tapers back down to the detection limit. The source is similar to the situation encountered in the Brazos, sewage plant effluent upstream as well as increased surface runoff due to high January river flows. The solids and TOC concentration in the water displayed expectedly increased values for samples obtained near the rivers during the wet season.

Copper dissolved in the water was detected as being above usual concentrations in May around the Brazos and San Bernard Rivers. This increase was apparently due to the unusually high flooding conditions at the time of sampling. A slight increase was also detected in the vicinity of the Colorado River in January for copper and zinc.

Cadmium values in the sediment increased somewhat in the areas surrounding both the Colorado and Brazos Rivers in January. This could be due to the various types of influent waters these rivers receive upstream from towns and their related industries. Higher values for zinc and lead were also detected near the Brazos River. Zinc was found to be high in both the water and sediment of the Brazos River. Values for all four metals in the sediment at the Brazos River agreed well with other studies conducted in this area (Slowey, et al, 1973).

Data obtained for lead and zinc correlated well with previous values in the San Bernard River area (Slowey, et al, 1973). It should be noted that the metals concentration in this river was much less than in the Brazos River.

The concentration of lead and copper found in the sediment of Matagorda Bay, agreed closely with unpublished data obtained from the Bureau of Economic Geology at the University of Texas. In this study a rise in the concentration of lead in the sediment was detected surrounding mi. 462.

Sediment samples obtained in Corpus Christi Bay did not indicate any significant problem areas. Metals concentration problems that have affected the nearshore harbor areas have apparently not spread to the other side of the bay. Zinc values in the bay were somewhat higher than those found in the GIWW. These values, however, agreed with previous

Civil Engineering Department data (Withers, et al., 1973). The lead concentration encountered in the bay was in the same range as had been previously reported by U.S. Geological Survey Data for 1974.

Reach Three - Corpus Christi Bay to Brownsville

The third reach extends from the Corpus Christi Bay area to near Port Isabel, a distance of 153 miles (mile 538 to mile 690). Low rainfall values of 26 to 30 inches (660.4 to 762 mm) per year characterize this semi-arid stretch. The GIWW is protected by Padre Island which extends along its entire length. This barrier island is typified by high sand dunes and sparse vegetation. Three major bay areas are located along this area, upper and lower Laguna Madre as well as Baffin Bay. The Laguna Madre averages only 2 to 3 feet (0.61 to 0.91 m) in depth.

A unique characteristic of the Laguna Madre is the lack of marsh areas and presence of extensive mudflat areas. It is believed that high salinity values in the soil are chiefly responsible for the lack of vegetation in these areas. Large areas of submerged vegetation, however, provide most of the biological productivity in the area. Salinity is a major factor in the biological productivity. Natural hypersalinity has been reduced in recent years by construcion of ship channels and the GIWW. Salinity values prior to this construction often exceeded 60.

Dissolved oxygen, pH, temperature, Eh, and turbidity data remained fairly constant throughout the reach with variations occurring only in localized areas.

The data shows slightly elevated levels of ammonia, nitrates and nitrites around the intersection of the Arroyo Colorado and GIWW, Figures 14, 15 and 16. When samples were obtained upstream in the Arroyo Colorado, an increase in the concentration of one or more of these parameters was also detected. Since this waterway serves as the connecting channel to Port Harlingen and other small towns and leisure homes along its shores, numerous opportunities exist for domestic wastes to enter the channel. None of the nutrient values were found to be excessive in this reach.

Of the metals analyzed in this third reach only copper and zinc displayed definite peaks, Figures 20 and 22. Both of these metals varied considerably along the section showing simultaneous peaks at several different locations. Zinc values in the GIWW near Baffin Bay show a small rise in both the water and sediment. An area bordered by Port Mansfield and the Arroyo Colorado exhibited values higher than those typically found in the area for these two metals in both the water and sediment. Since several small towns are located along the Arroyo including Port Harlingen, they could be a source of metals input through runoff. In addition to these two metals, lead and cadmium also exhibited a rise in this same area.

TABLE 4.--Mileage-Location Correlation.

GIWW Mileage	Location Reference
265.4	Sabine River about 6.6 mi. (10.62 km) upstream from Sabine Lake
276.6	Neches River
278.0	Sabine Lake
285.0	Port Arthur
290.0	Taylor Bayou Outfall Canal
305.4	Spindletop Gully
315.0	Oil Well Slough
320.5	East Bay Bayou
329.8	Opening to East Galveston Bay
342.5	Bolivar Peninsula
350.2	Intersection of GIWW and Houston Ship Channel
353.4	Galveston Bay
358.2	West Galveston Bay
374.0	Near Chocolate Bay
395.4	Near Freeport
400.8	Brazos River
405.0	San Bernard River
428.4	Opening of East Matagorda Bay into GIWW
440.7	Harbor at Matagorda
441.5	Colorado River
453.5	Opening of Oyster Lake into GIWW
460-471.2	Matagorda Bay
479.0	Opening of Espiritu Santo Bay into GIWW
492-498.4	San Antonio Bay
517-524.2	Aransas Bay
530-536.3	Redfish Bay
542-548.8	Corpus Christi Bay
555.6	Upper Laguna Madre
580.8	Baffin Bay
631.4	Near Port Mansfield--Lower Laguna Madre
646.0	Arroyo Colorado
670.0	Port Isabel

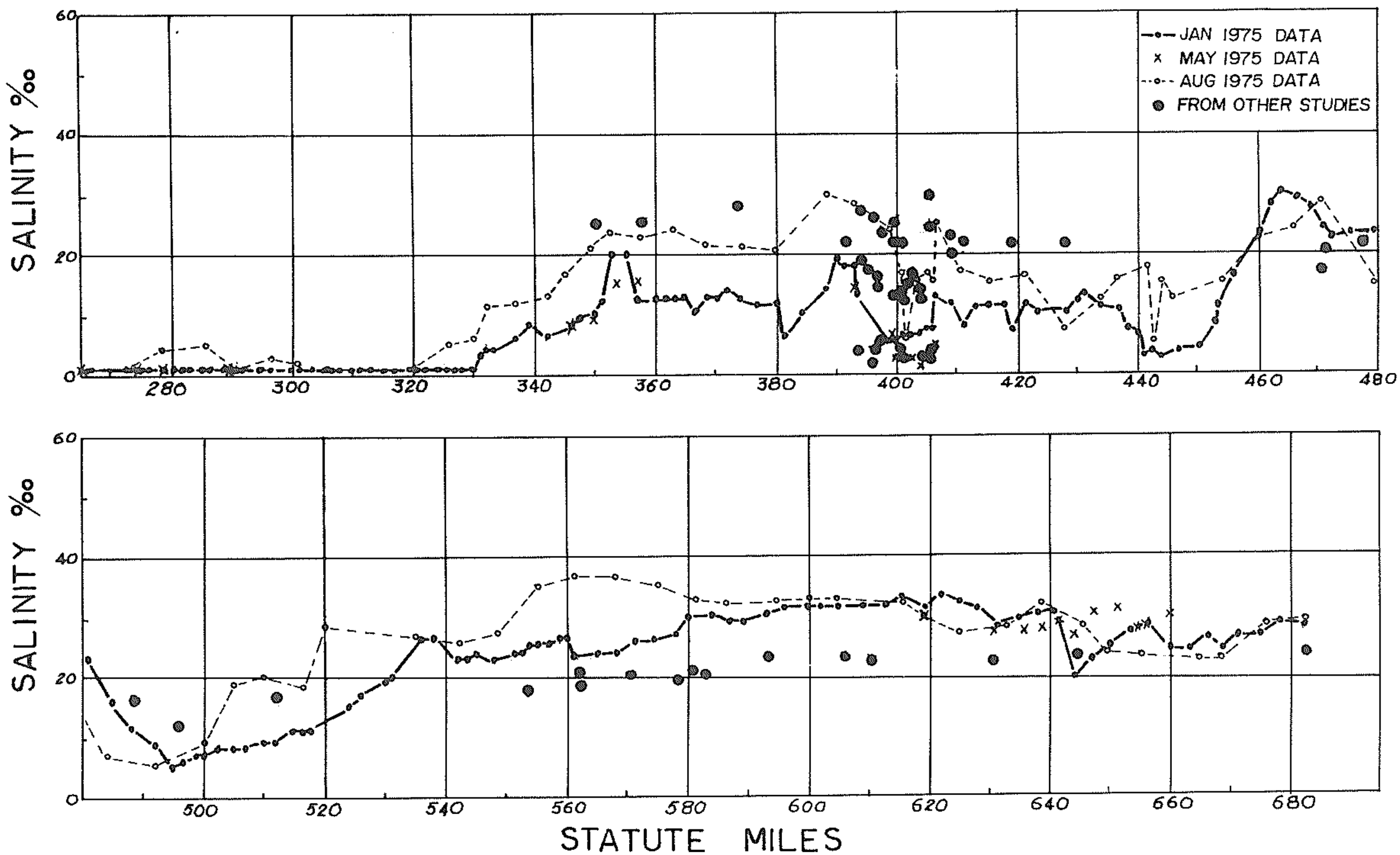

Figure 8. Surface Water Salinity

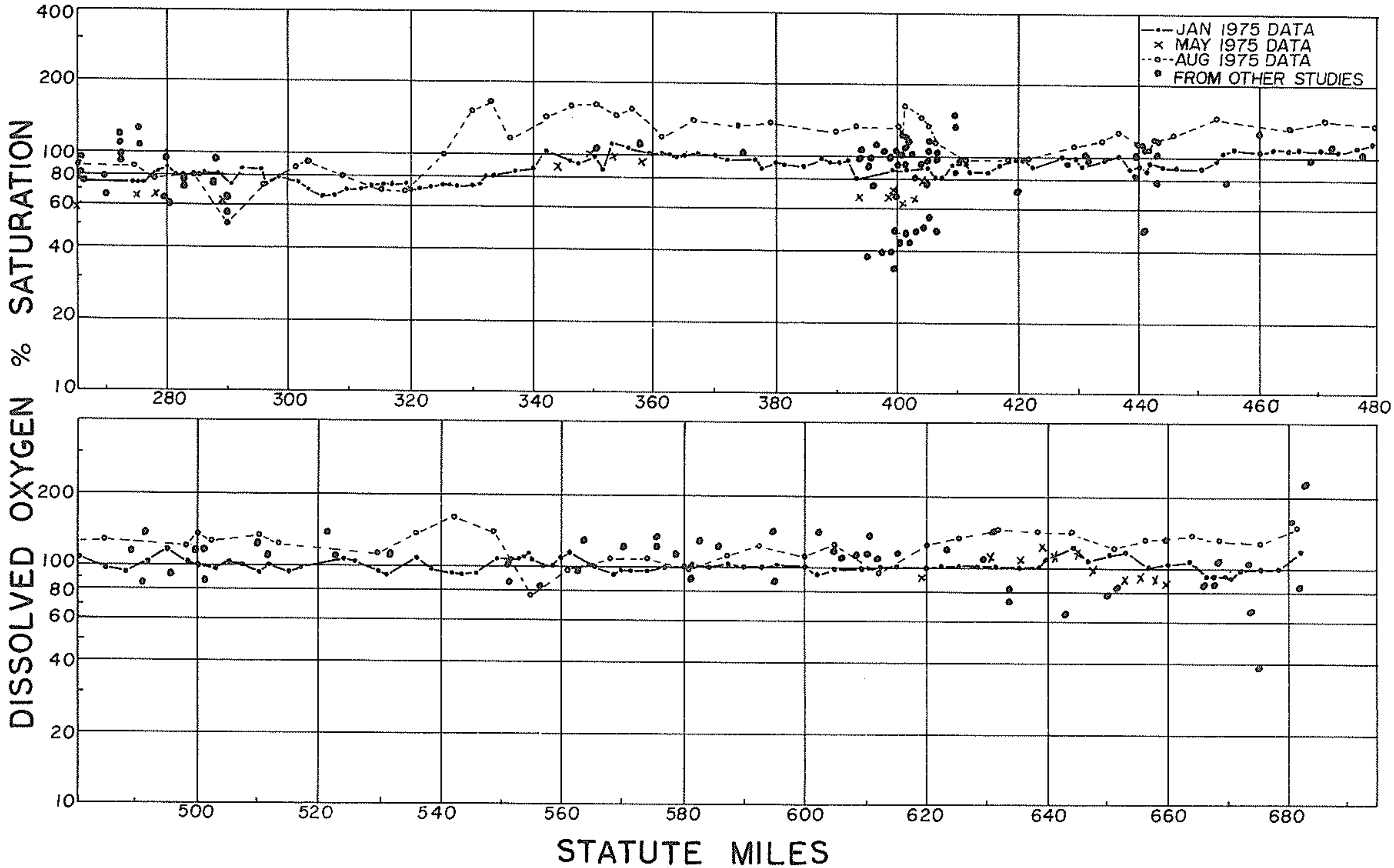

Figure 9. Surface Percent Saturation Dissolved Oxygen

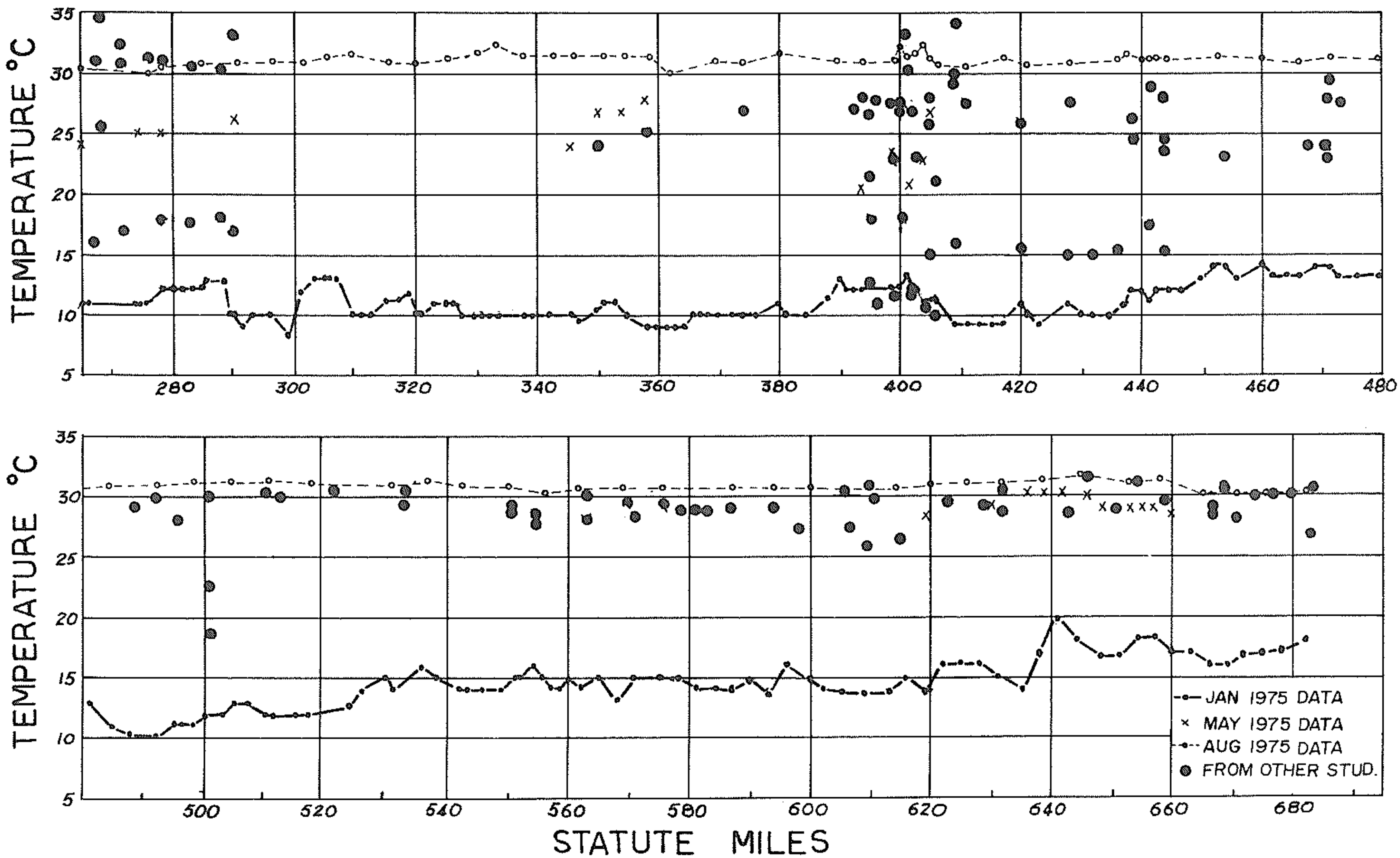

Figure 10. Surface Water Temperature

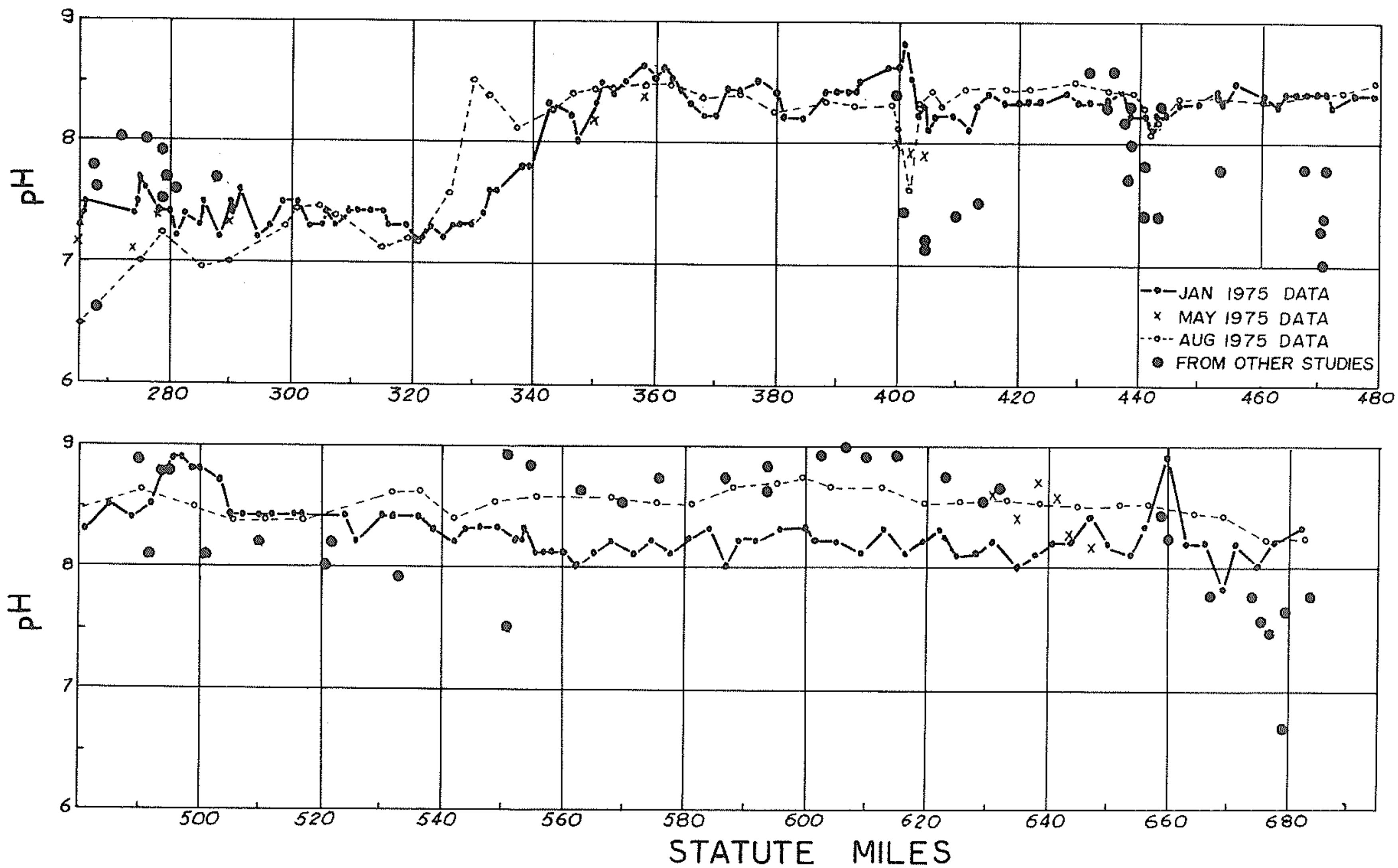

Figure 11. Surface Water pH Values

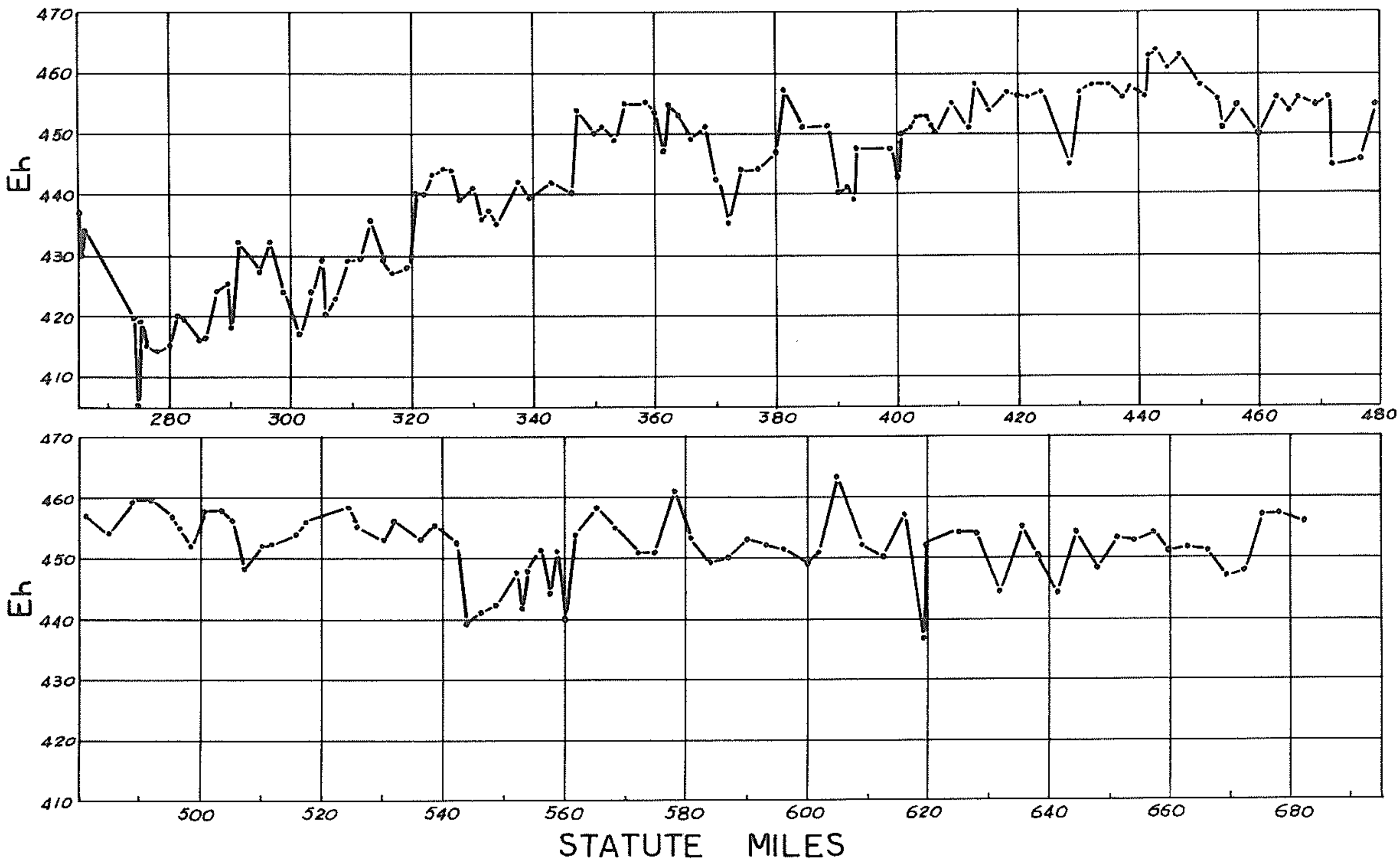

Figure 12. Surface Water Eh Values in (mv)

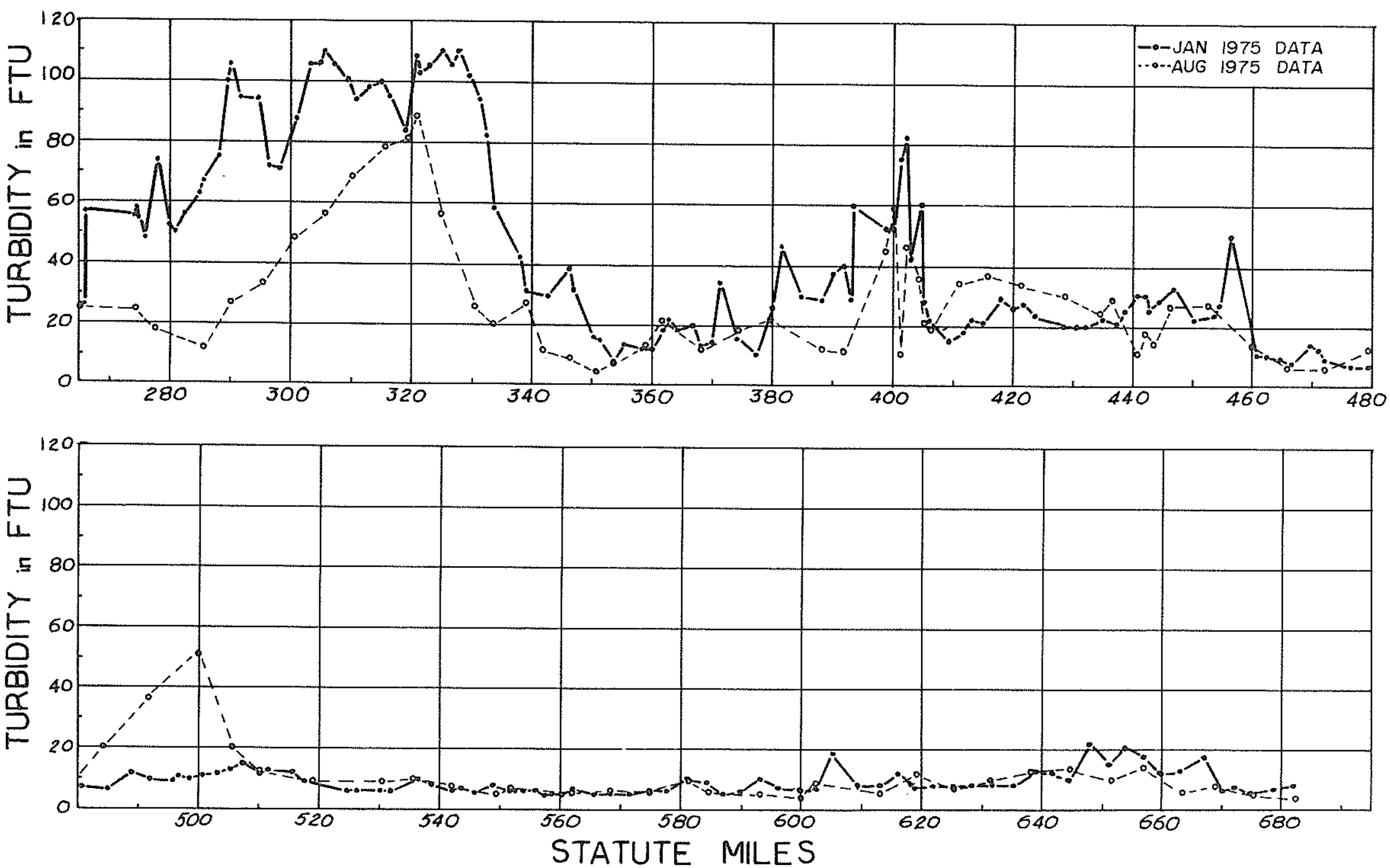

Figure 13. Surface Water Turbidity

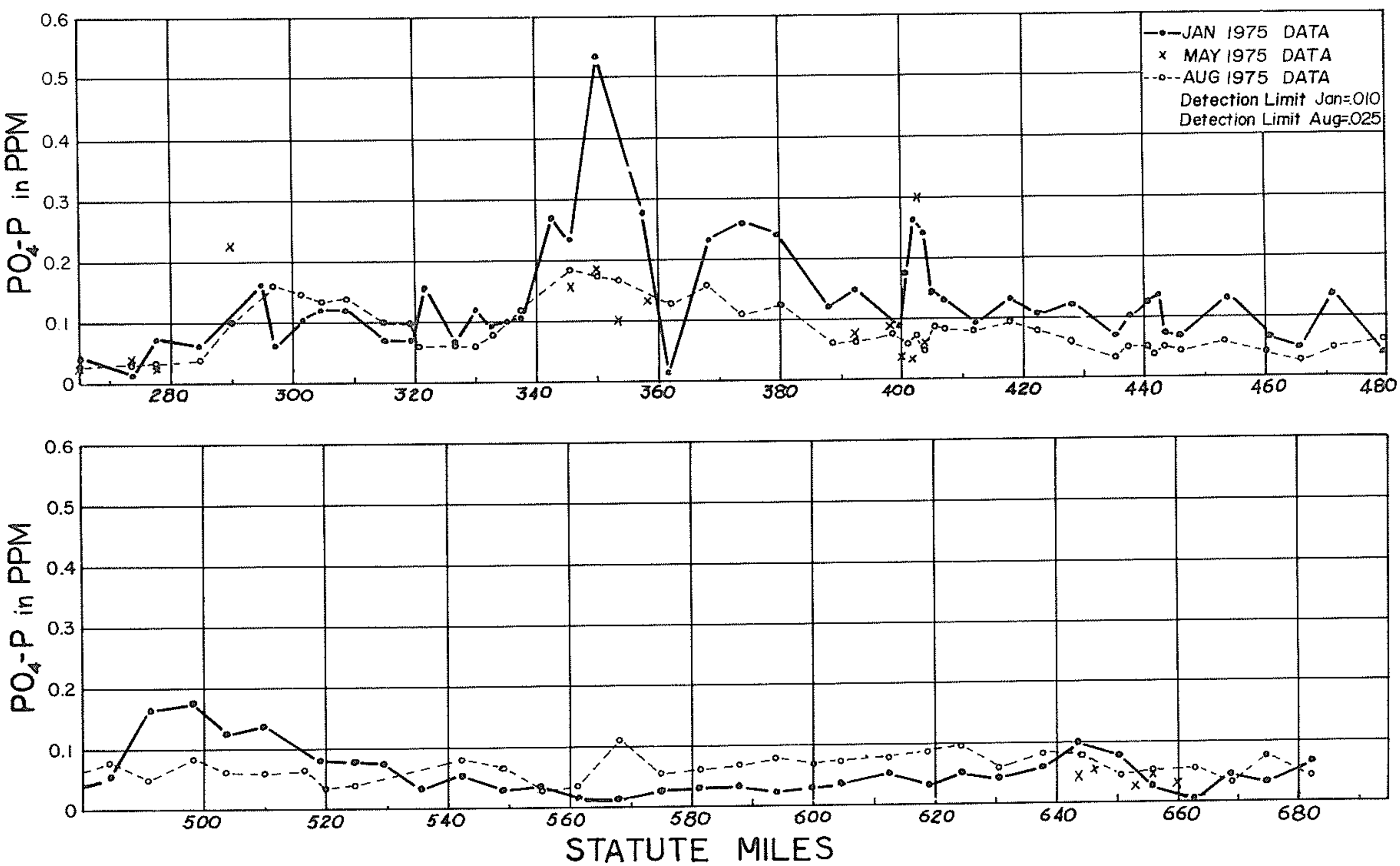

Figure 14. Middepth Phosphate Values

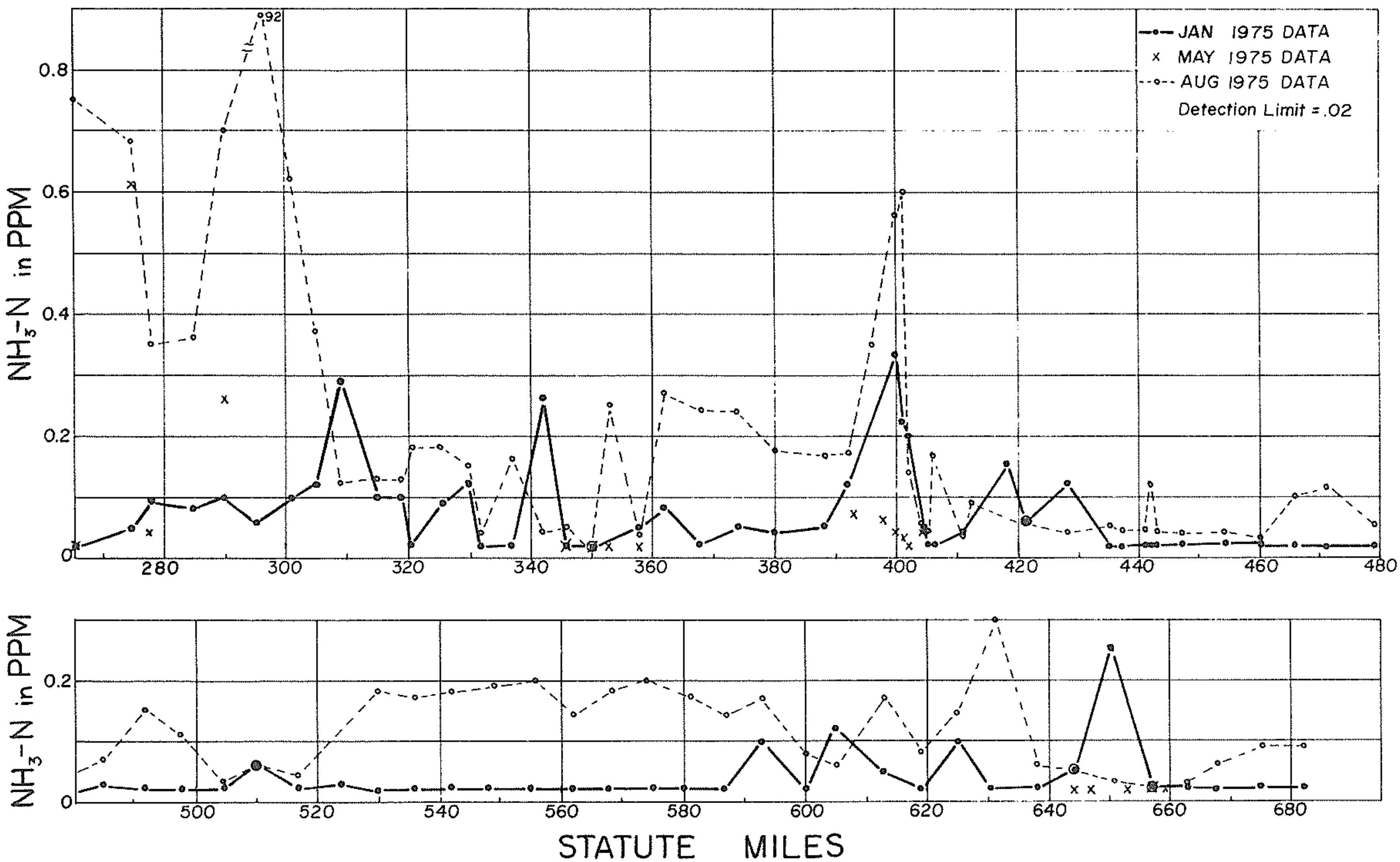

Figure 15. Middepth Ammonia Values

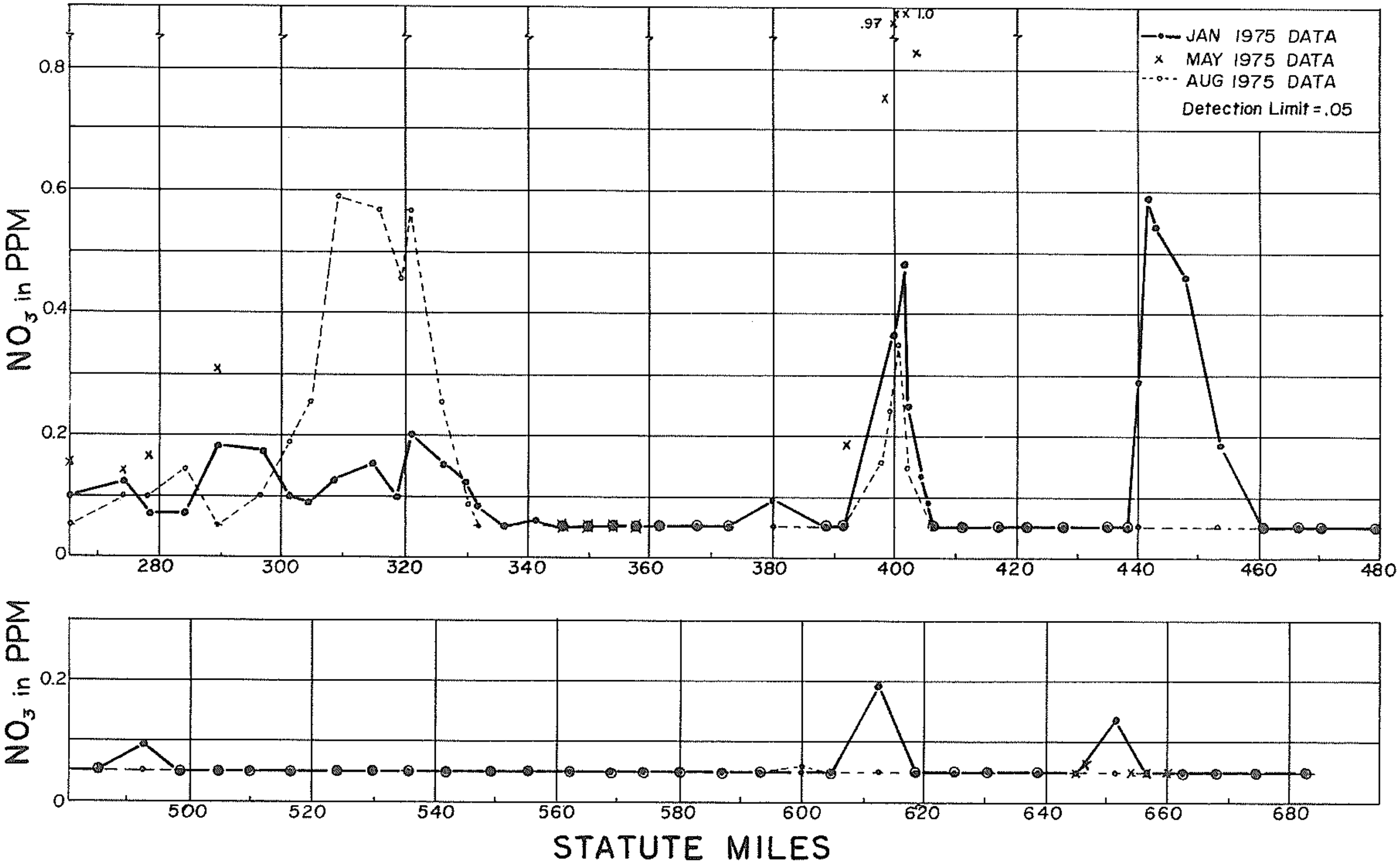

Figure 16. Middepth Nitrate Values

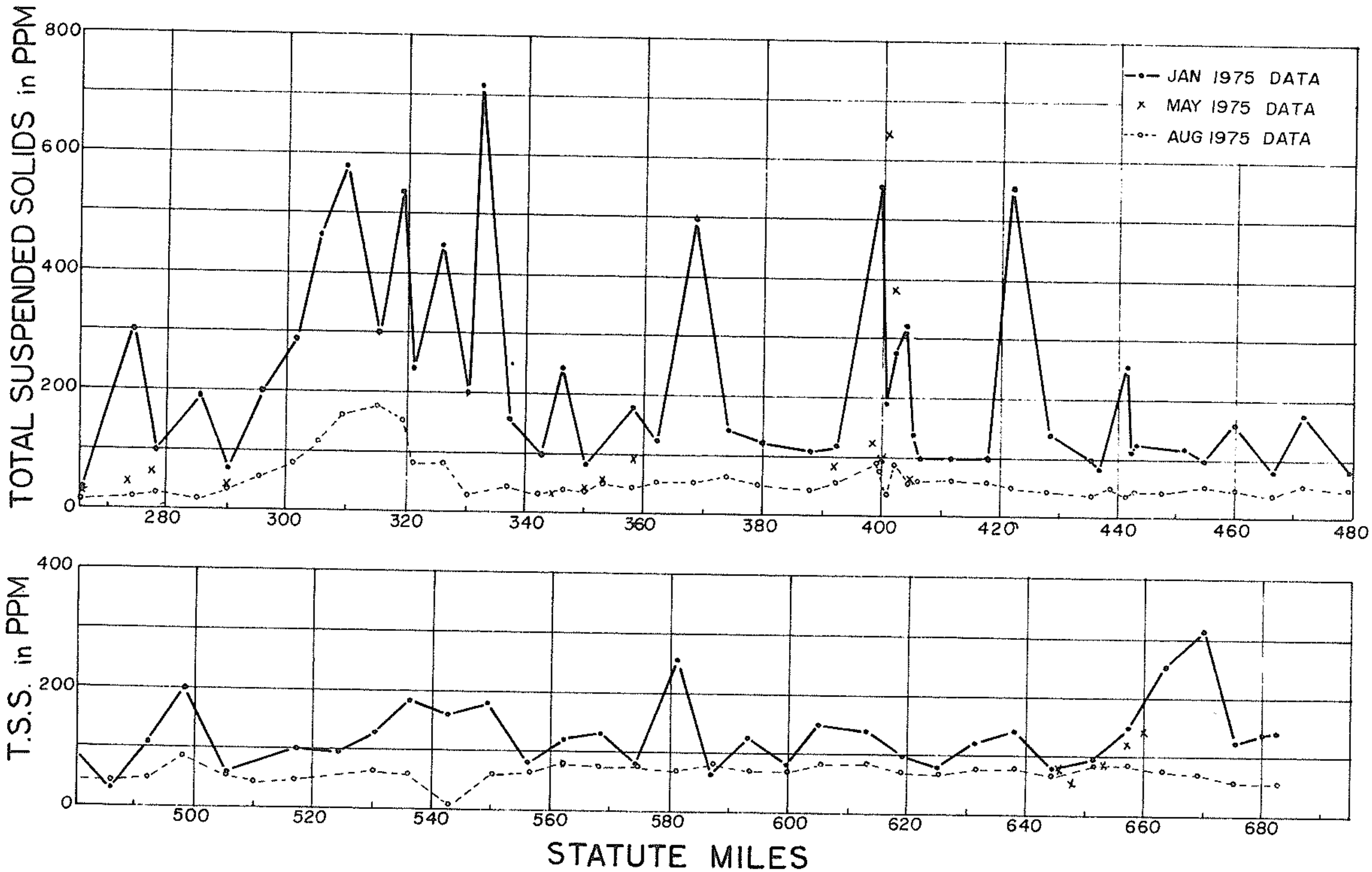

Figure 17. Total Suspended Solids

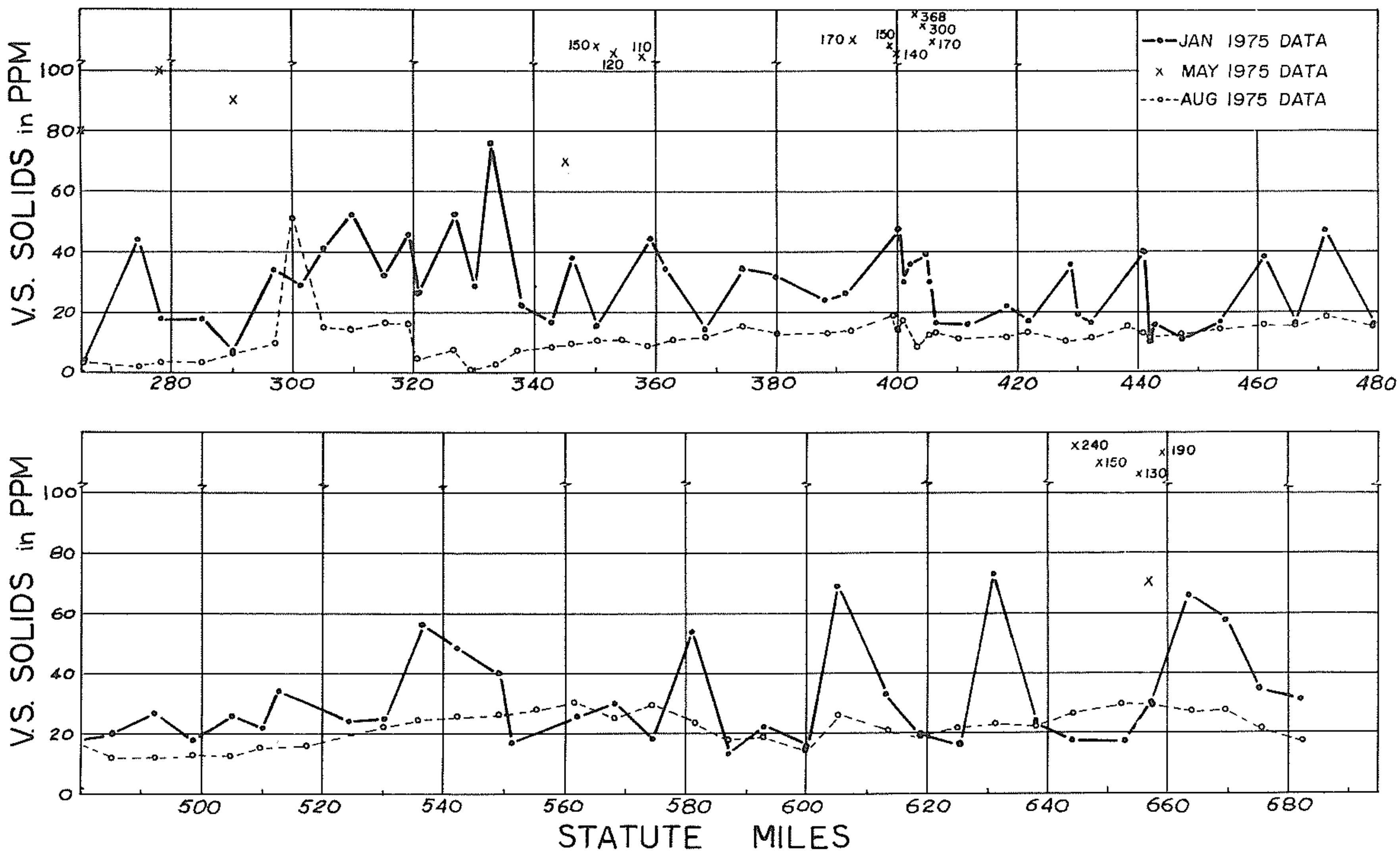

Figure 18. Middepth Volatile Suspended Solids

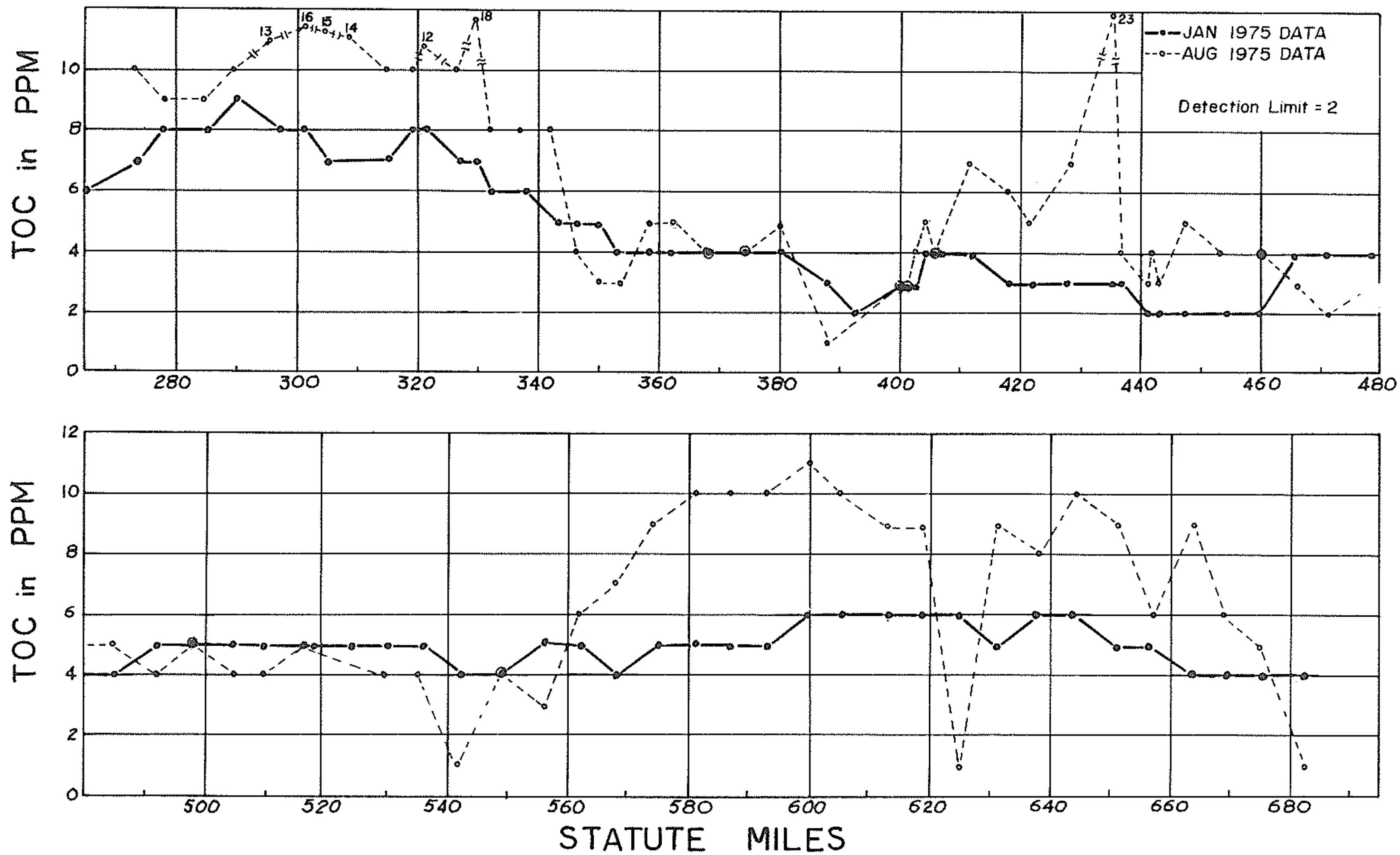

Figure 19. Middepth Total Organic Carbon

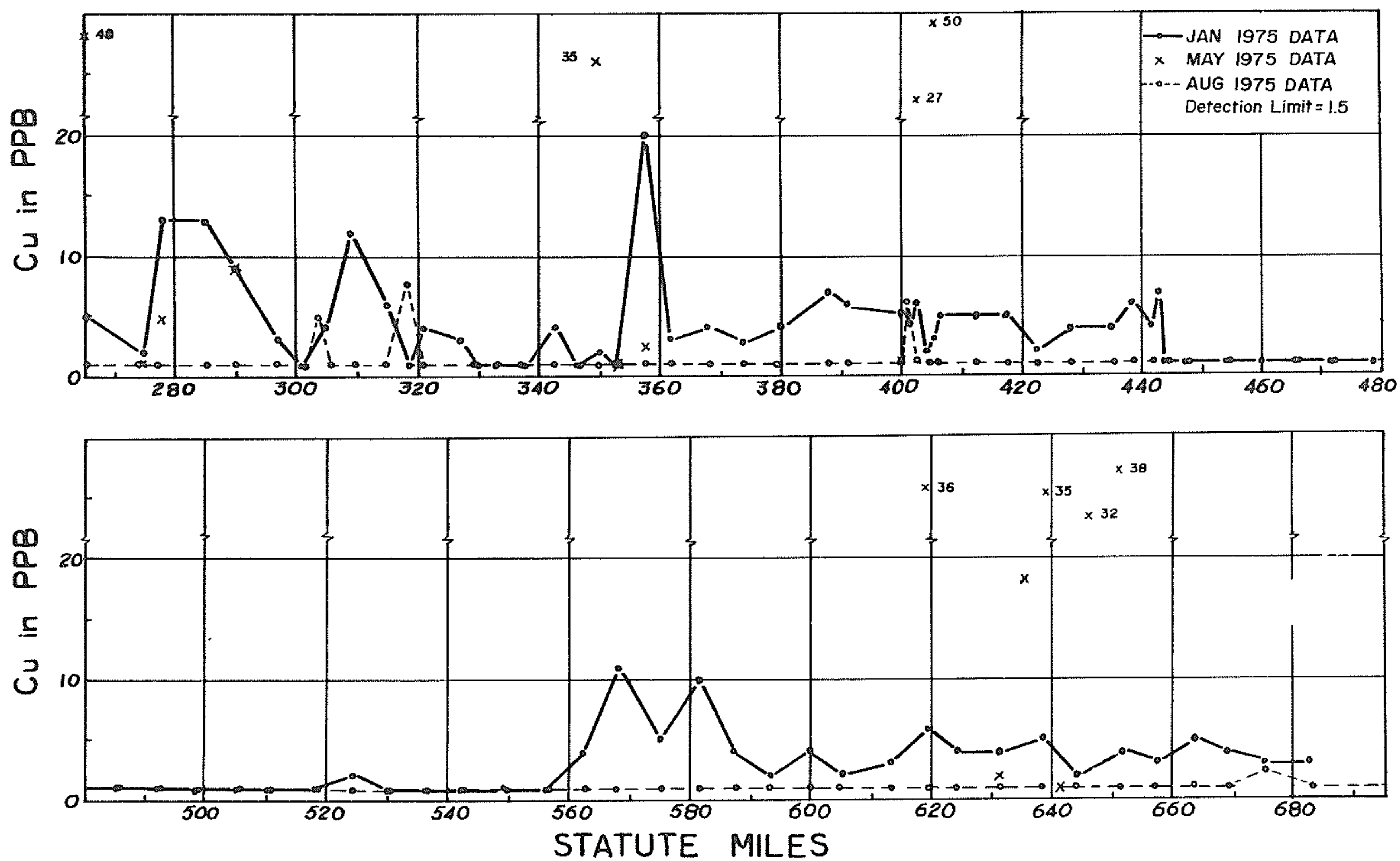

Figure 20. Middepth Values of Copper in Water

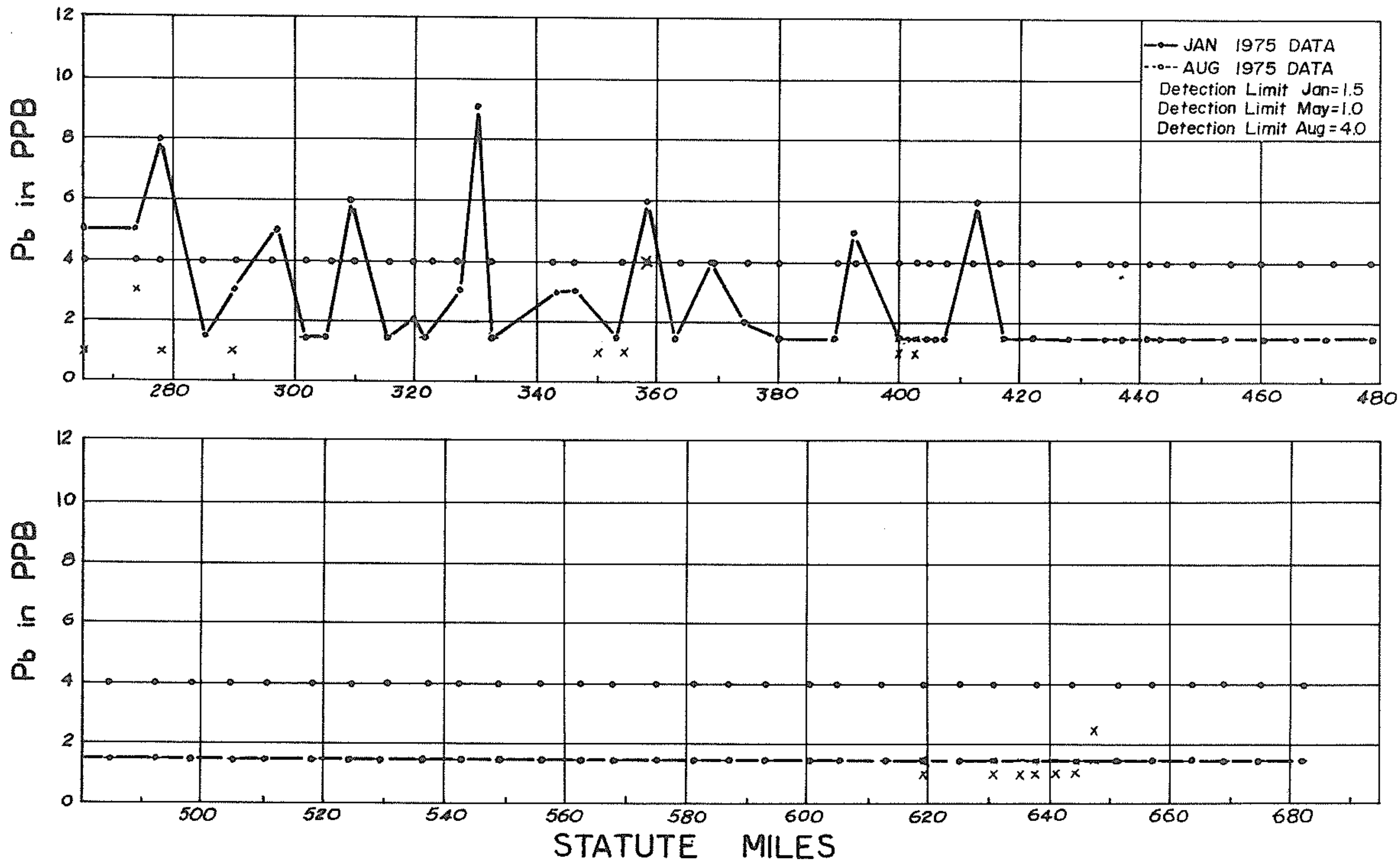

Figure 21. Middepth Values of Lead in Water

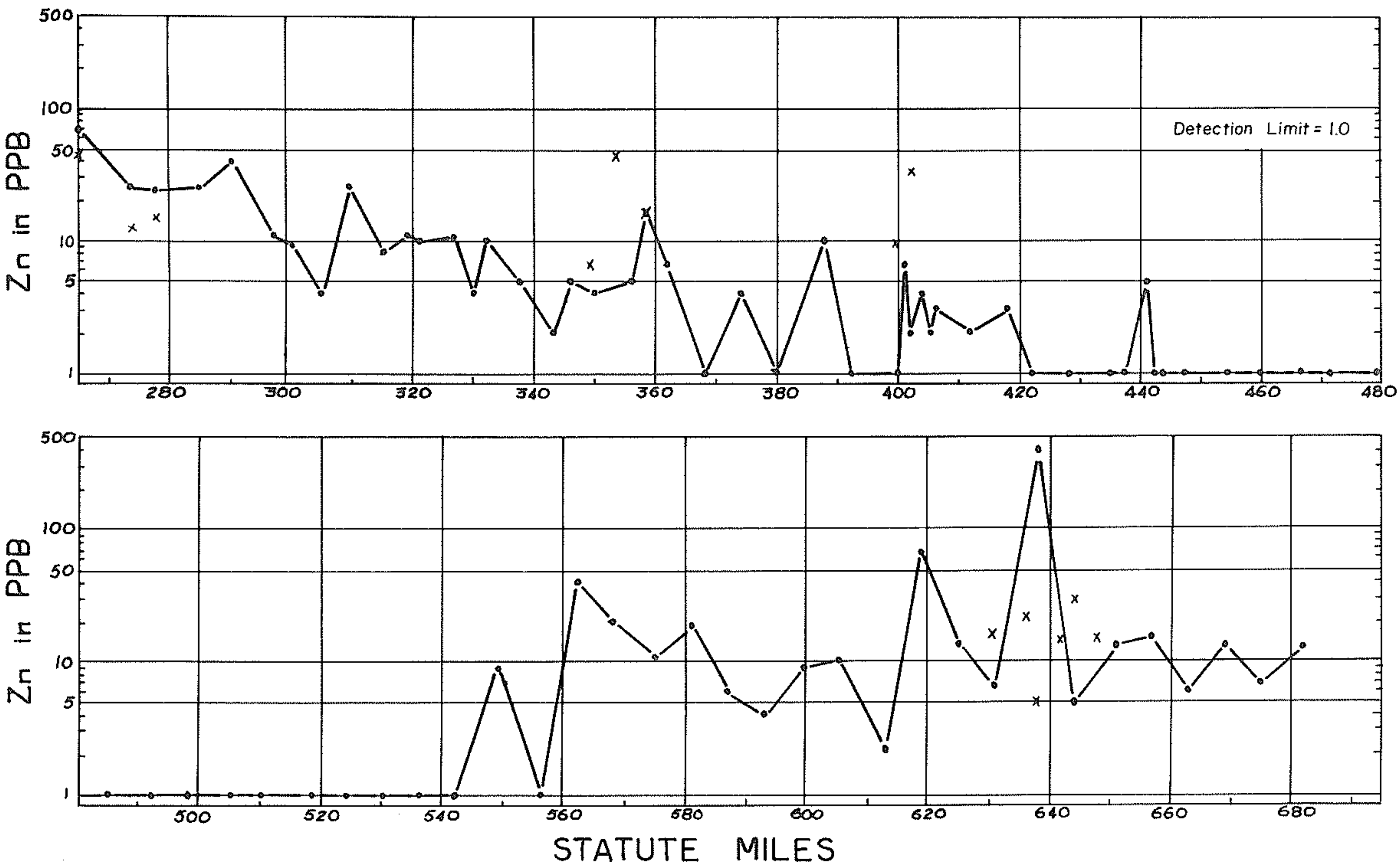

Figure 22. Middepth Values of Zinc in Water

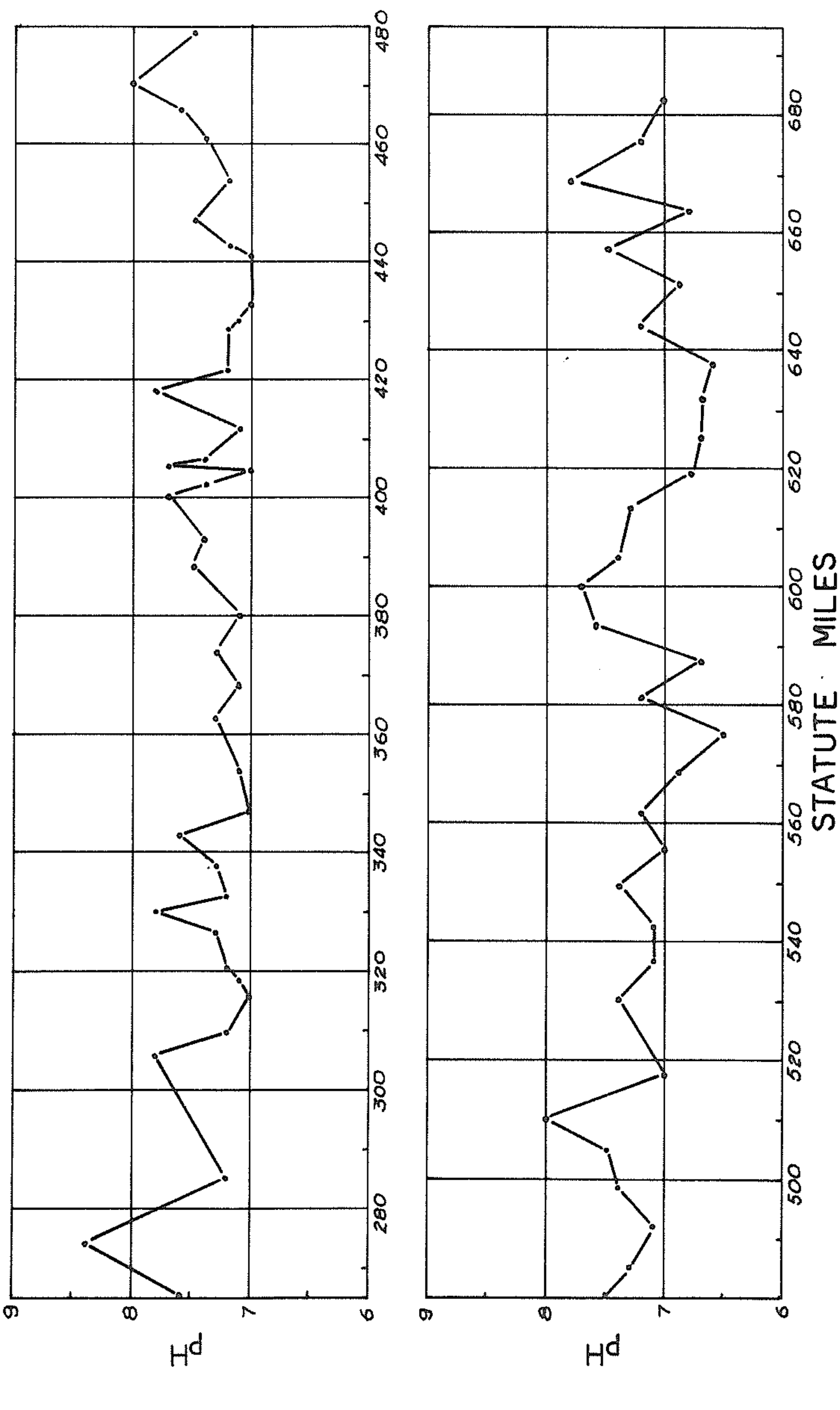

Figure 23. pH in Sediments

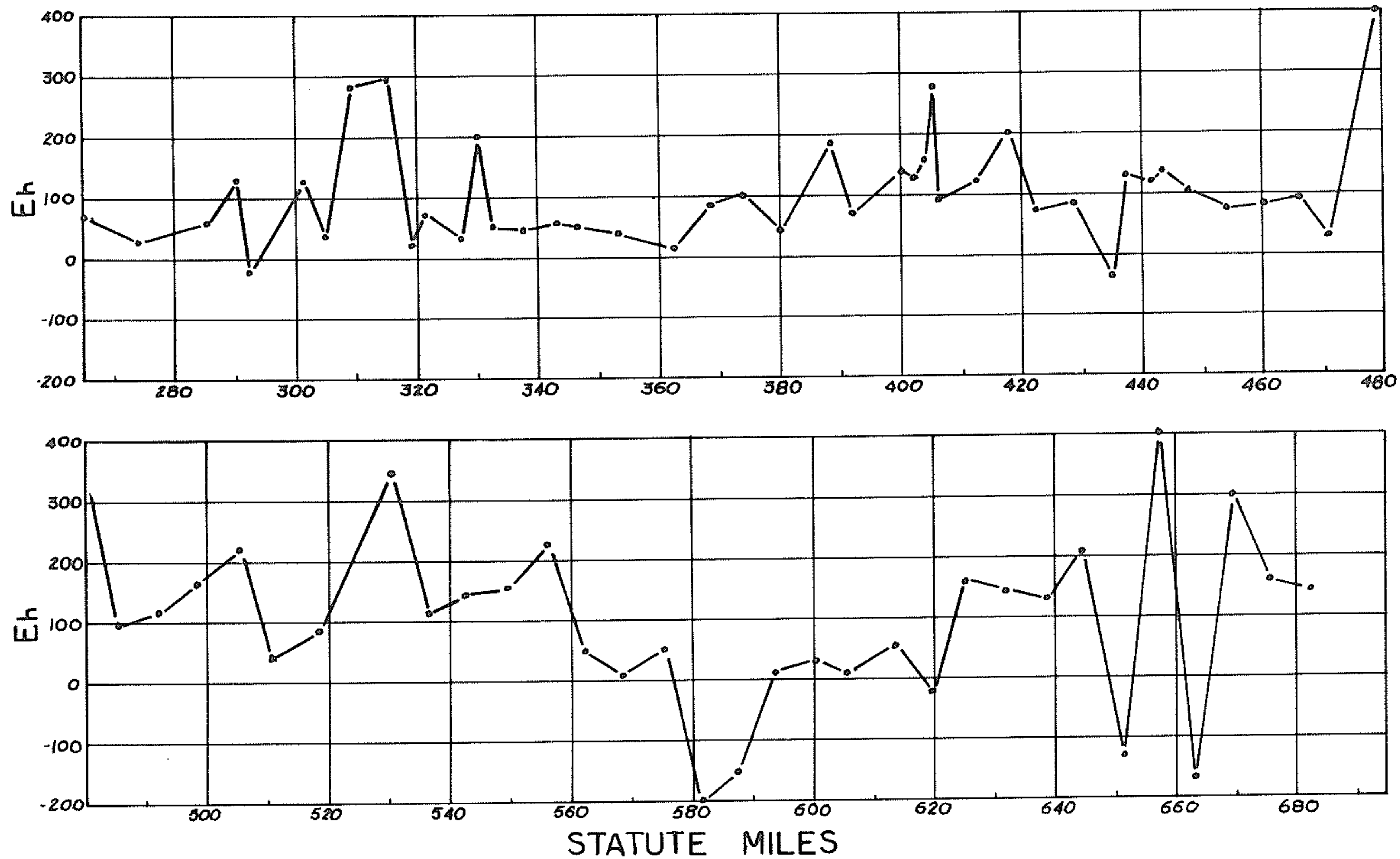

Figure 24. Eh in Sediments

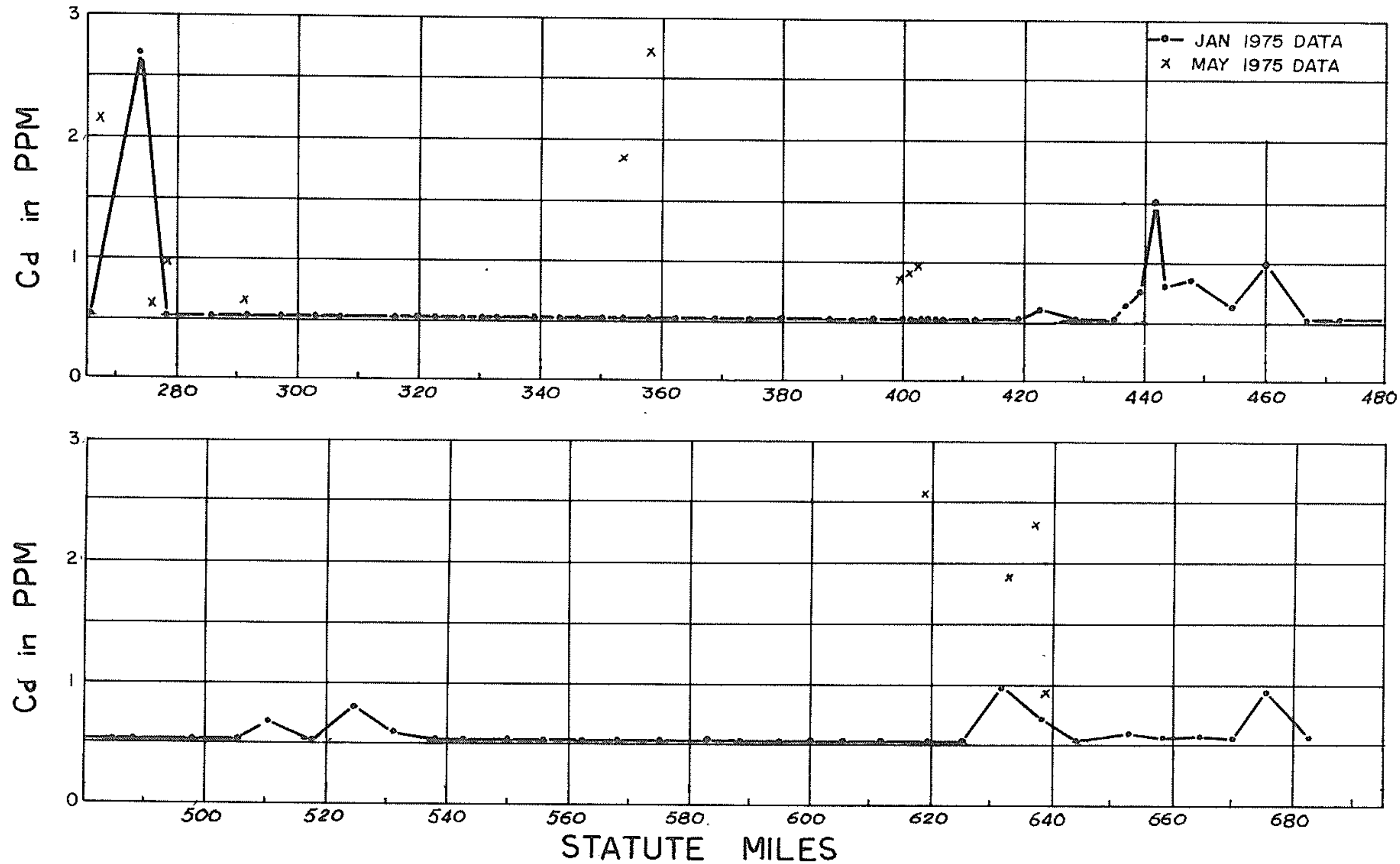

Figure 25. Cadmium in Sediments

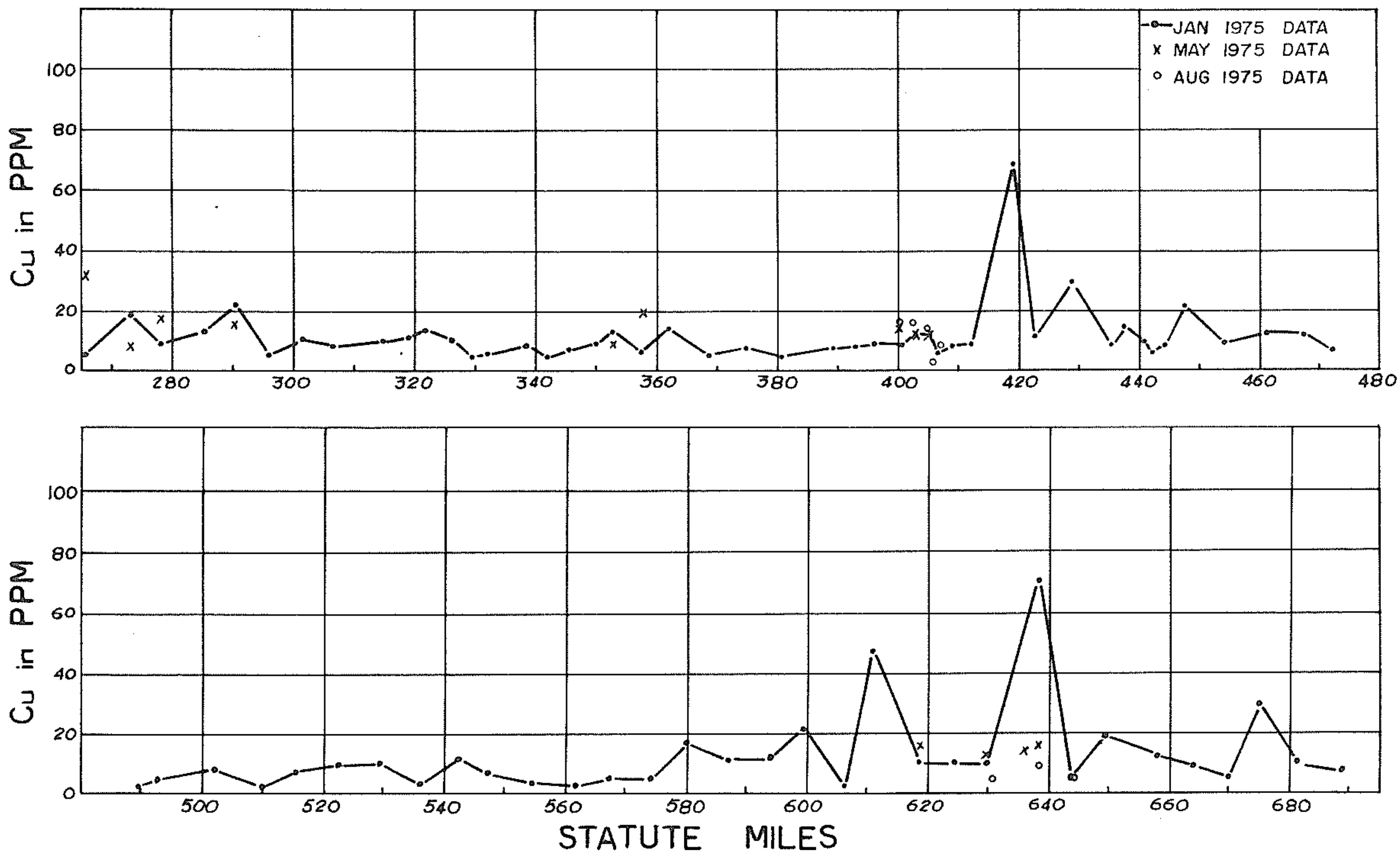

Figure 26. Copper in Sediments

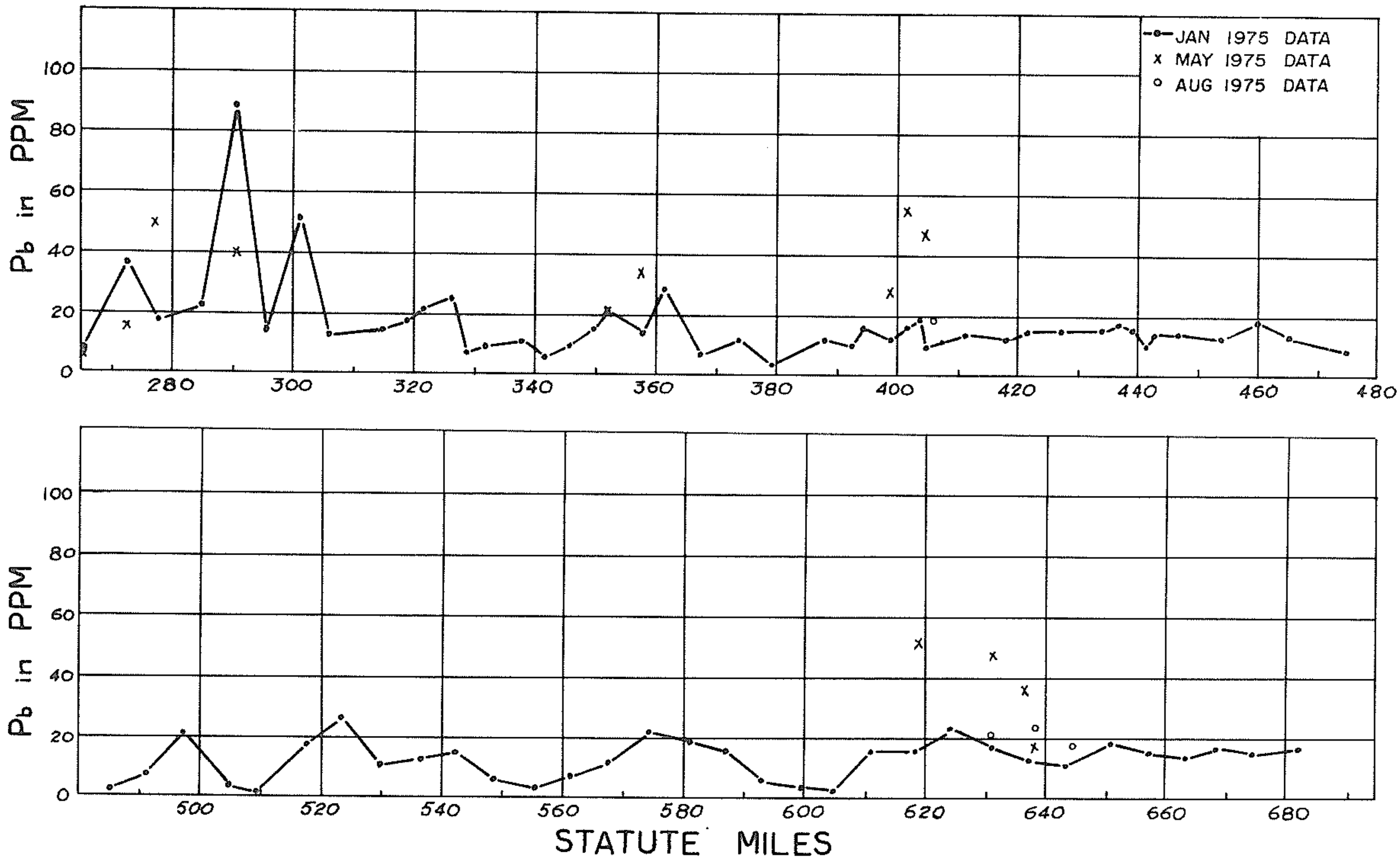

Figure 27. Lead in Sediments

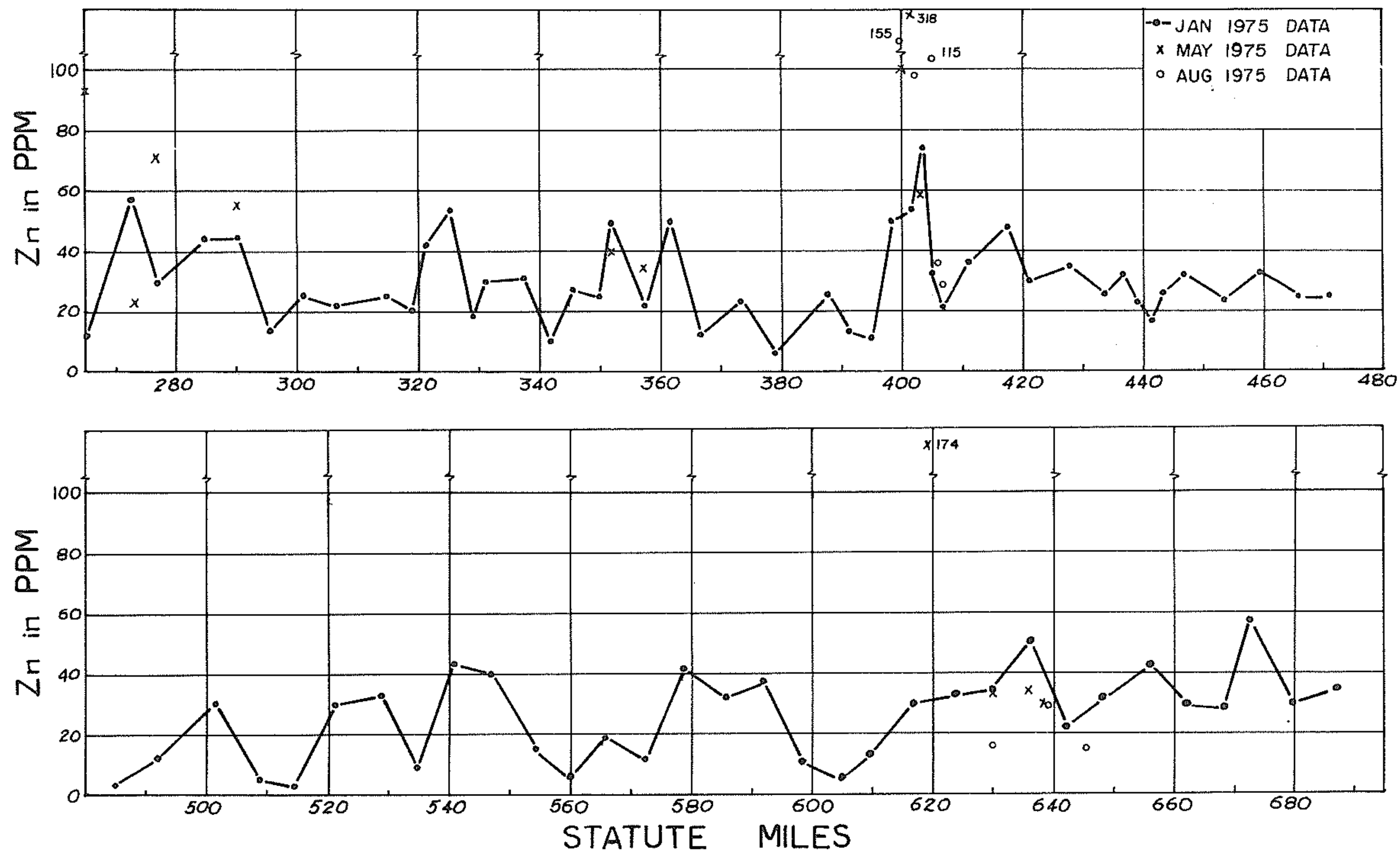

Figure 28. Zinc in Sediments

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CHAPTER IV

CIRCULATION STUDIES

Introduction

The movement of water from Lake Sabine to Galveston Bay and the circulation patterns in the Lower Laguna Madre are considered in this chapter. A one-dimensional hydrodynamic model was applied to the Sabine-Galveston Waterway system to evaluate the various factors affecting the flow of water between the two bays. The model was calibrated from field measurements made during this study.

A Sea Grant study conducted by Atturio, et al. (1976) indicated extremely high sedimentation for one section of the waterway in the Lower Laguna Madre. Satellite imagery was obtained of the Lower Laguna Madre and the circulation patterns were analyzed to evaluate the cause of the high shoaling rate at this location.

Flow From Sabine Lake to Galveston Bay

Statement of the Problem

It appears that much of the time water in the Sabine Lake flows towards the Galveston Bay through the Gulf Intracoastal Waterway (GIWW). In this section, flow in the GIWW between Sabine Lake and the Galveston Bay will be analyzed by utilizing field data and a computer program (see Figures 29 and 30).

Description of the Area

The GIWW utilizes the channels of the Sabine-Neches Waterway from a point about 3 miles (4.8 km) below Orange through the Sabine River

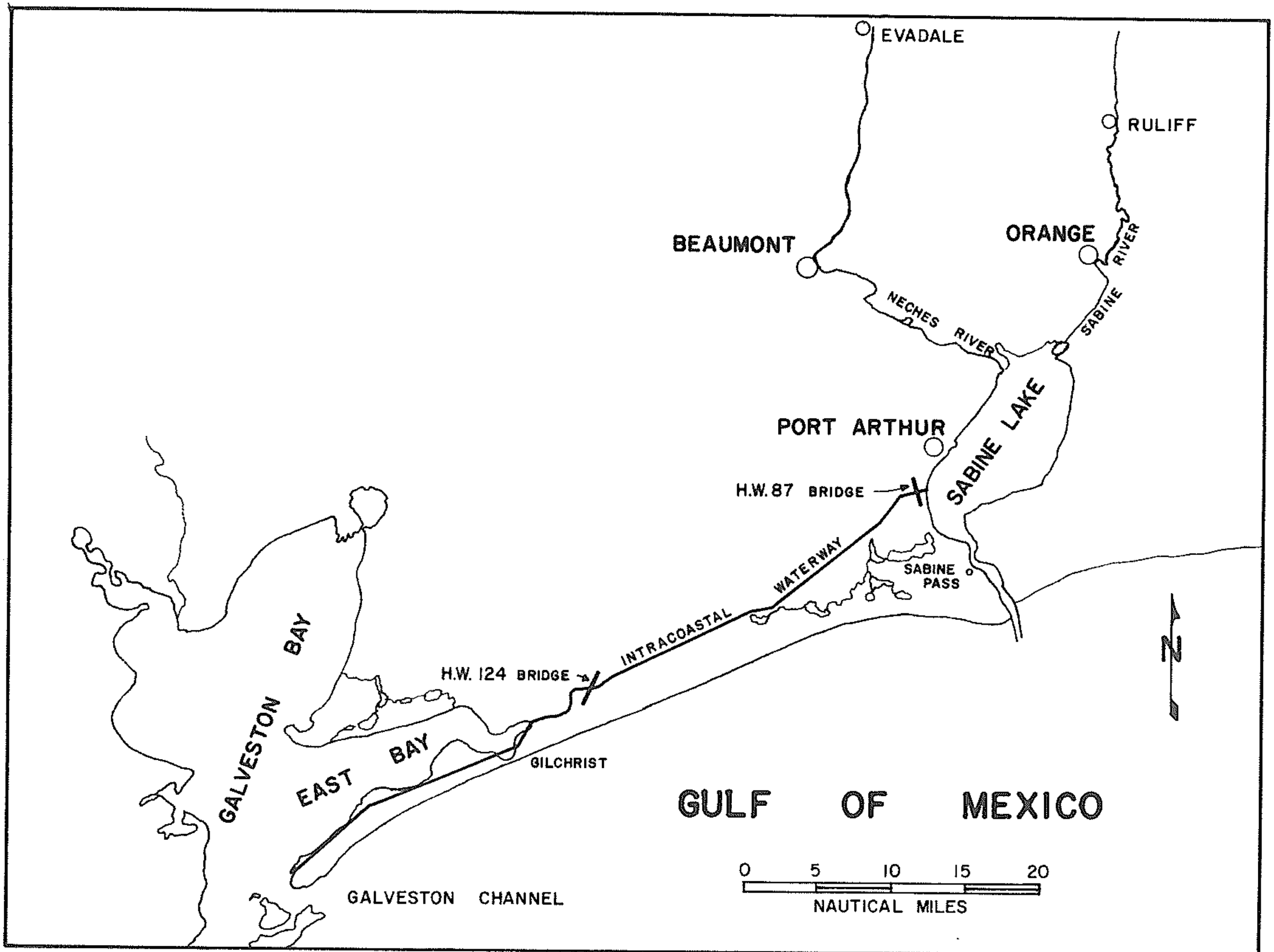


Figure 29. Location Map Sabine-Galveston Bay Reach

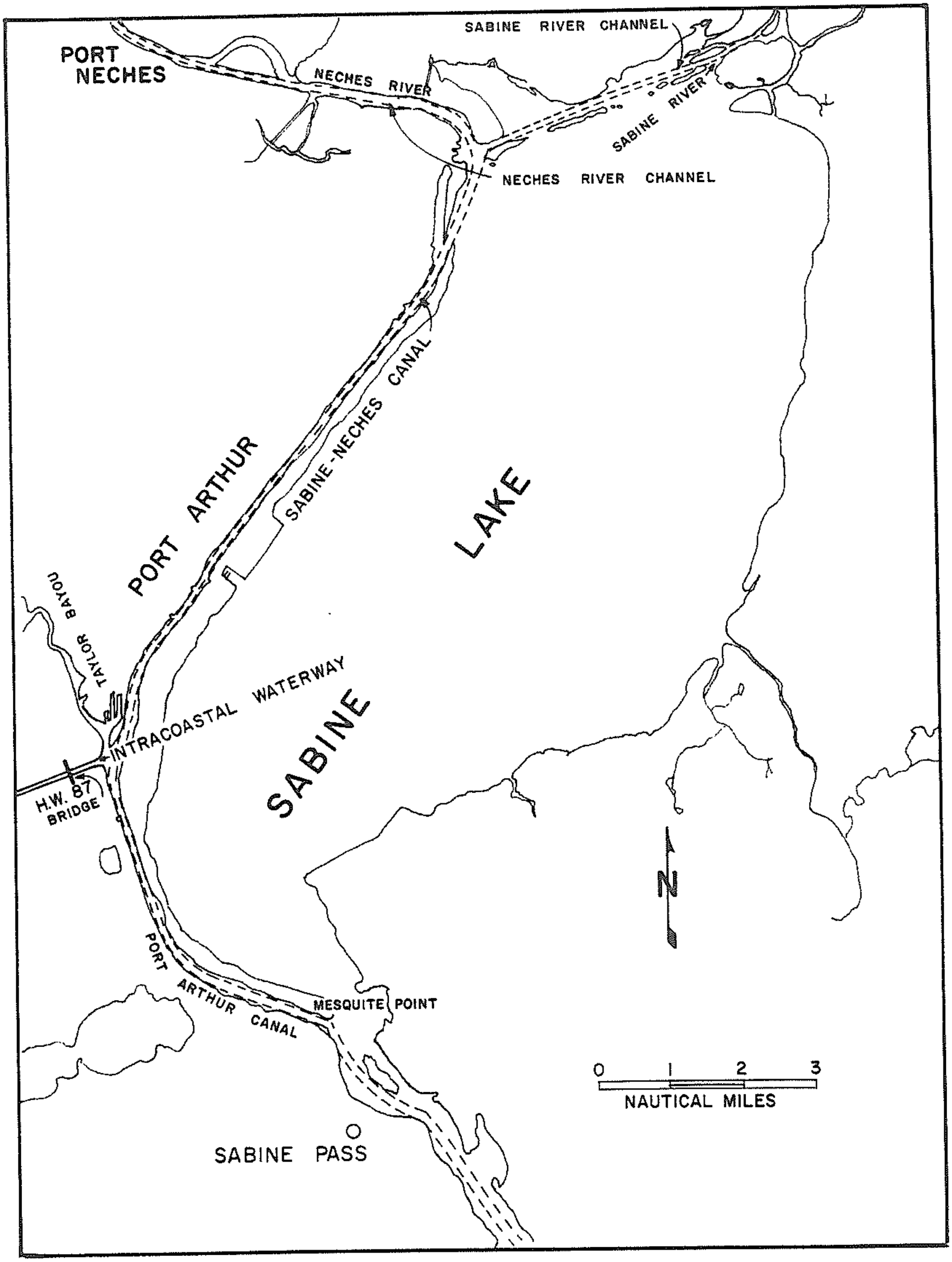


Figure 30. Sabine Lake Area.

and the Sabine-Neches Canal to the head of the Port Arthur Canal. The GIWW extends from the industrialized Port Arthur Canal, southwestward by land cut through marsh areas across Salt Bayou, Spindletop Gully, Seth Slough, Barnes Slough, Oil Well Slough, and the North Prong of Mud Bayou to the bridge on Texas Highway 124 near the community of High Island. Beyond High Island, the GIWW crosses a marsh area by land cut and follows the general downstream direction of East Bay Bayou by land cut. The channel then crosses a shallow section of East (Galveston) Bay, and proceeds into the grass marsh area of Bolivar Peninsula. The GIWW has a controlling depth of 12 ft (3.6 m) and a bottom width of 125 ft (38.1 m).

Sabine Lake is about 17 miles (27.4 km) long and has an average depth of about 6 ft (1.8 m). At the southern end, where it empties into Sabine Pass, depths of 19 to 30 ft (5.8 to 9.1 m) are available in a short narrow outlet channel. Sabine River, emptying into the Sabine Lake from the northeast, has a drainage area of 9,329 sq miles (24,152 sq km). Neches River, emptying into the Sabine Lake from the northwest, has a drainage area of 7,951 sq miles (20,584 sq km).

Sabine Pass, on the boundary of Texas and Louisiana, is the natural outlet from the Sabine Lake to the Gulf of Mexico. The Port Arthur and Sabine-Neches Canals are artificial channels that have been dredged along the shore of Sabine Lake. Port Arthur Canal extends from Sabine Pass to the entrance of Taylor Bayou. A narrow strip of land separates the canal from the western shore of Sabine Lake. Sabine-Neches Canal, a continuation of the Port Arthur Canal above the mouth of Taylor Bayou, parallels the shore of Sabine Lake west of the Neches River. Beyond the Neches River, the canal crosses a narrow neck of land through a 0.5 mile (0.8 km) cut and continues eastward across the upper end of Sabine Lake to the mouth of the Sabine River.

Factors Causing Flow in the Waterway

Except during storms, freshwater inflow from small bayous into the GIWW between the Sabine Lake and the Galveston Bay is negligible. This reach is tidal, tides propagating from Sabine Pass and Galveston Bay. Therefore the GIWW between the Sabine Lake and Galveston Bay can be considered as a canal connecting two tidal seas. The following four factors were considered to be responsible for creating flow in a canal connecting two tidal seas. They are:

1. Astronomical tide. Tides of different phase and amplitude propagating from the tidal seas would create flow in the canal.
2. Wind set-up. Due to differences in wind set-up in the two tidal seas, flow can be created.
3. Freshwater inflow. Large freshwater flow into one of the tidal seas would raise sea level in that sea creating flow in the canal.
4. Wind stress. Wind acting on the surface of the water in the canal would create flow in the canal.

In the following section, those four factors would be considered.

Astronomical Tide

Tides propagating from Sabine Pass go up the Port Arthur Canal and into the GIWW. The Sabine-Neches Waterway is tidal throughout its length with a mean diurnal range of about 2.2 ft (0.67 m) at the Gulf entrance and 1.0 ft (0.30 m) at Port Arthur.

Tide tables compiled by the National Oceanic and Atmospheric Administration indicate the tides at Mesquite Point lag behind those at Sabine Pass by 50 to 56 minutes. The propagation speed of tide (c) is related to the water depth (d) and the acceleration of gravity (g) by the equation

$$c = \sqrt{gd} \tag{1}$$

Port Arthur Canal has a controlling depth of 40 ft (12.2 m) between Port Arthur and Mesquite Point. Substituting g = 32.2 ft/sec^2 (9.81m/sec^2) and d = 40 ft (12.2 m) into the above equation, gives c = 35.89 ft/sec (10.9 m/sec) which gives a travel time of 14.6 minutes for the tides to reach Port Arthur after passing Mesquite Point (distance between Port Arthur and Mesquite Point is taken as 31,500 ft (9,600 m)). Consequently, it is estimated that the tides at Port Arthur lag behind those at Sabine Pass by 65 to 71 minutes, and those at Galveston Channel by 10 to 11 minutes (according to tide tables, tides at Sabine Pass lag those at Galveston Channel by 1.0 hours at high water and by 1.25 hours at low water). As can be seen in the later sections of this chapter, this estimate seems to be quite reasonable.

According to tide tables, tides at Gilchrist, East Bay lag those at Galveston Channel by 3.27 hours at high water and by 4.3 hours at low water. Time lag of this range was also confirmed by Prather and Sorensen (1972). In this study it was estimated that tides at the location where the GIWW meets East Bay lag those at Galveston Channel by 3 to 4 hours.

Wind Set-Up

Because of small tidal variations in the area under consideration, wind set-up is expected to have a significant and direct effect upon the water level differential at the two ends of the canal and therefore the flow through the canal.

In Table 5, wind set-up in Sabine Lake at the northern end of the lake is calculated for various wind speeds and directions. The equation used is (Ippen, 1966):

$$S_i = h_i \left[\left[\frac{2NkU^2X}{gh_i^2} + 1 \right]^{1/2} - 1 \right] \tag{2}$$

where:

S_i = incremental rise over the i^{th} section

U = wind speed

h_i = total water depth in the i^{th} section

k = 3.3×10^{-6}

N = the platform factor which takes into account changes in the bottom depth and section width.

X = length of section

The nodal point at which no set-up occurs is assumed to be in the middle of the bay, i.e., $X_{node}/L = 1/2$ or $X = L/2$ where L = the total fetch length.

For computation purposes, Sabine Lake is considered to be a closed rectangular basin of constant depth. The following measurements were made from a map of Sabine Lake:

Wind Direction	Fetch Length, L (ft)	(m)	Average Depth, d (ft)	(m)
N-S	55,700	16,980	6	1.83
NNW-SSE	49,800	15,180	6	1.83
NW-SE	39,400	12,010	7	2.13
NWW-SEE	32,000	9,750	6	1.83
W-E	31,500	9,600	5	1.52

Assuming that the depth is constant for wind set-up across the entire lake, the equation becomes:

$$S = d\left[\left[\frac{2XkU^2}{gd^2} + 1\right]^{1/2} - 1\right] \qquad (3)$$

During the period of December 13th through 24th, 1973, strong winds shifted direction along the Texas coast. Figure 31 shows the wind record taken at Buccaneer platform together with the tide record at North Sabine Lake. As can be seen in Figure 31, after the wind shifted direction from the north to the south, water started piling up at North Sabine Lake. After the wind shifted direction from the north to the south, the water level at North Sabine Lake was set down by more than one foot (0.3 m). This is in a good comparison with values given in Table 5. Also, it was reported that prolonged southerly winds raise the water level in the channels around Sabine Lake by several feet (U.S. Corps of Engineers, 1959).

It is estimated that wind set-up at Port Arthur can reach one foot (0.3 m) for a strong wind of 30 to 40 knots (15.4 to 20.6 m/sec), and wind set-up of several inches can easily be attained by moderate

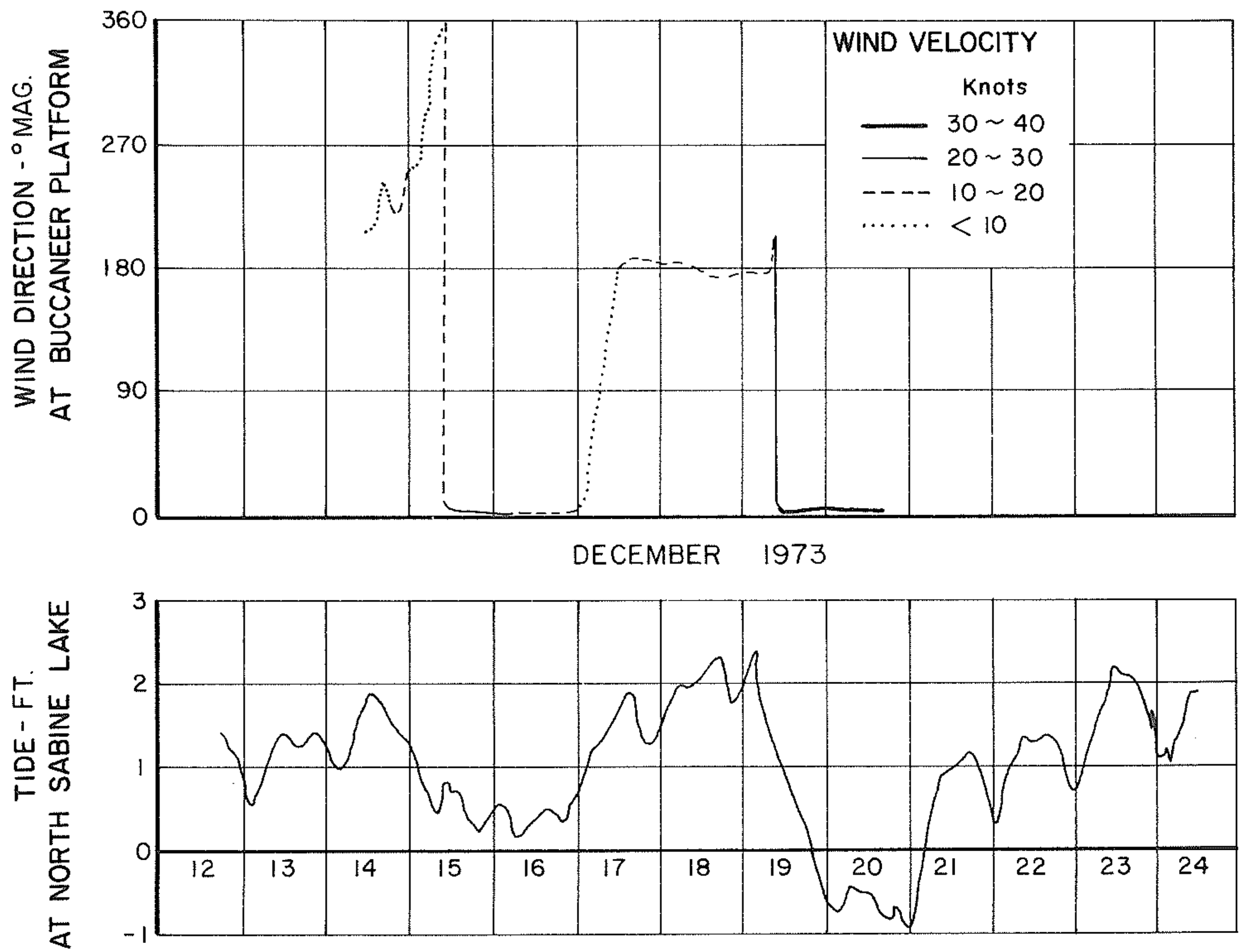


Figure 31. Wind Record at Buccaneer Platform and Tide Record at North Sabine Lake.

Table 5. Computed Wind Set-Up Values in Feet for the North Sabine Lake.

WIND SPEED IN KNOTS	WIND DIRECTION N-S	NNW-SEE	NW-SE	NWW-SEE	W-E
5	0.03	0.03	0.02	0.02	0.02
10	0.13	0.12	0.08	0.08	0.09
15	0.30	0.27	0.18	0.17	0.20
20	0.52	0.47	0.32	0.30	0.36
25	0.80	0.72	0.50	0.47	0.55
30	1.12	1.01	0.71	0.66	0.77
35	1.48	1.34	0.94	0.89	1.02
40	1.88	1.70	1.21	1.14	1.30

winds.

Wind set-up in Galveston Bay is difficult to estimate due to the irregular shape of the bay. The normal water surface elevation at the Galveston Channel has been lowered by amounts up to 4.3 ft (1.3 m) by strong northerly winds and similar wind set-up was observed at other locations in the bay (U.S. Corps of Engineers, 1971).

Since they are expected to have different wind set-ups, Port Arthur and East Bay could have a difference in water levels of 1.0 ft (0.30 m) under normal conditions. During hurricanes wind set-up could reach more than 10 ft (3.0 m) causing most of the low-lying areas along the GIWW to be flooded. Cases during hurricanes will not be considered in this study.

Freshwater Inflow

Two major sources of freshwater into the Sabine Lake are the Sabine and Neches River. During the period of 1968 through 1972, the Sabine River at Ruliff had a highest monthly mean flow rate of 33,240 cfs (940 cms) and a lowest value of 292 cfs (8 cms) with a median value of 3,355 cfs (95 cms). For the same period, the Neches River at Evadale had a highest monthly mean flow rate of 24,120 cfs (680 cms) and a lowest value of 373 cfs (10 cms) with a median value of 2,417 cfs (68 cms).

Sabine-Neches Canal has a controlling depth of 40 ft (12.2 m) and a width of 400 ft (122 m). Neches River Channel is 40 ft (12.3 m) deep and 400 ft (122 m) wide to Beaumont via the Neches River, while Sabine River Channel is 30 ft (9.1 m) deep and 200 ft (61.0 m) wide to Orange via the Sabine River. The northern end of Sabine Lake, where the Sabine

River Channel meets Sabine Lake. is very shallow (3 to 4 ft (0.9 to 1.2 m)). Consequently, a large percentage of the freshwater inflow from the Sabine and Neches Rivers follows the Sabine-Neches Canal to Port Arthur, then Port Arthur Canal which has a controlling depth of 40 ft (12.2 m) and a width of 500 ft (152 m).

Floods on the Neches River and Sabine River cause rises of short duration varying up to about 13.6 ft (4.15 m) at Beaumont and 7.6 ft (2.32 m) at Orange (U.S. Corps of Engineers, 1959). Even under normal conditions, small fluctuations in freshwater inflow from the Sabine and Neches Rivers could raise the water level at Port Arthur by several inches.

Wind Stress

Wind stress acting on the surface of the water in the canal would cause flow in the canal. However, this effect is considered to be insignificant compared to the effect of the other factors considered previously.

Procedures

In the previous sections, four factors which could cause flow in a canal were considered. The effect of wind set-up and that of freshwater inflow into one of the tidal seas are similar in that they create flow in a canal by creating differences in water level in two tidal seas.

Flow problems in a canal connecting two tidal seas have received consideration ever since sea-level canal was proposed (Harleman & Lee, 1969). Various hydrodynamical numerical models have been applied to compute tides and currents in canals. Harleman and Lee (1969) developed a one-dimensional hydrodynamical model by using an explicit finite difference scheme, and their model was applied to different canals and estuaries. The model developed by Harleman and Lee can be applied to a canal connecting two tidal seas, and was used in this study (brief description of the numerical model can be found in Appendix D).

The numerical model developed by Harleman and Lee takes instantaneous water levels at both ends of a canal as input and would give instantaneous heights of water surface and flow rate at selected locations along the canal.

In applying any numerical models to real estuaries and canals, field data are required to verify and calibrate the models used. As a part of this study, field measurements were conducted from March 18, 1976 through March 20, 1976 during which period typical semi-diurnal tides occurred along the Texas coast. Tides were measured at Highway 87 fixed bridge, which is located near Port Arthur at Mile 288.7 and at the Highway 124 swing bridge located near High Island. By using a hydro product Savonius current meter, currents were measured at the Highway 87 bridge from a small powered boat. A current meter of the same type was used at the Highway 124 bridge to measure currents.

Tides measured at the Highway 87 bridge were assumed to represent tides at the Port Arthur side of the canal. Tides at the Galveston side of the canal were estimated from the tides measured at Port Arthur. Tides at Port Arthur and at the Galveston side of the canal constituted input data to the numerical model, and instantaneous height of water surface and flow rate at selected locations along the canal were computed by the numerical model. The height of water surface and flow rate computed by the numerical model at High Island were compared with the field data obtained at High Island. Flow rates computed by the model at Port Arthur were compared to that measured at Port Arthur.

The effects of wind set-up and freshwater inflow were represented as differences in water level at both ends of the canal.

After the numerical model was calibrated, different conditions were tested as input data to analyze possible effects of the four factors considered previously.

Tide Measured and Input Tide for the Numerical Model

Tides at Galveston Channel during the period of the field measurements are presented in Table 6. There is a duration of 7 hours between high tide and low tide for March 18 through March 19. It was assumed that the same duration between high tide and low tide exists at Port Arthur during the same period. Based on the considerations on tidal propagation in Port Arthur Canal presented in an earlier section of this chapter, it was assumed that high tide occurs at 17:00 Central Standard Time (CST) on March 18, 1976. Fitting a sine curve to the tides measured at Port Arthur for the period of 17:00 (March 18) through 0:00 (March 19) gives a difference of 1.061 ft (0.323 m) between high and low tides, while tides at Galveston Channel had a difference of 1.30 ft (0.396 m). The ratio of tidal amplitude at Port Arthur to tidal amplitude at Galveston Channel becomes 0.816. Using a tidal amplitude ratio of 0.816 and shifting times of high and low tide by nine minutes earlier than those in Galveston Channel, tide at Port Arthur for the period of March 18 through March 20 was estimated. The tide at the Galveston

Table 6. Predicted Tide at Galveston Channel.

DAY	TIME CST	HEIGHT FT
March 18	0626	1.4
TH	1209	0.6
	1709	1.1
19	0009	-0.2
F	0739	1.4
	1307	0.8
	1734	1.1
20	0104	-0.3
	0402	1.3
	1414	1.0
	1804	1.1

Heights are referenced to mean low water and are from the NOAA 1976 Tide Tables.

side of the canal was estimated by assuming the same tidal amplitude used at Port Arthur and setting the time of high and low tides occurring three hours later than the ones at Port Arthur. Tides thus estimated are presented in Figure 32 together with the measured tide at Port Arthur. These tides make up input tide for the numerical model.

Application of the Numerical Model

Schematization

The numerical model used in this study requires that the canal be divided into a discrete number of longitudinal segments and particular geometric characteristics be assigned to these segments.

A cross-section of the GIWW was measured at the Highway 124 bridge (High Island) and the measured cross-section is shown in Figure 33. It turned out that the depth of the GIWW reaches almost 20 ft (6.1 m) while the controlling depth is only 12 ft (3.7 m) with a bottom width of 125 ft (38.1 m). Similar results were obtained at the Port Arthur side of the canal where the cross-section of the canal was measured. In schematization, a uniform cross-section of 15 ft (4.6 m) deep and 200 ft (61.0 m) wide was selected to be used in the numerical model. The GIWW between Sabine Lake and Galveston Bay was assumed to be a straight canal with a horizontal bottom. A general layout of the canal used in the numerical model can be found in Figure 34. A reach of 36.25 miles (58.33 km) was divided into 12 segments. The highway 124 bridge (High Island) is assumed to be located at a two-segment distance 6.04 miles (9.72 km) from the Galveston side of the canal. The geometric data for the canal used are:

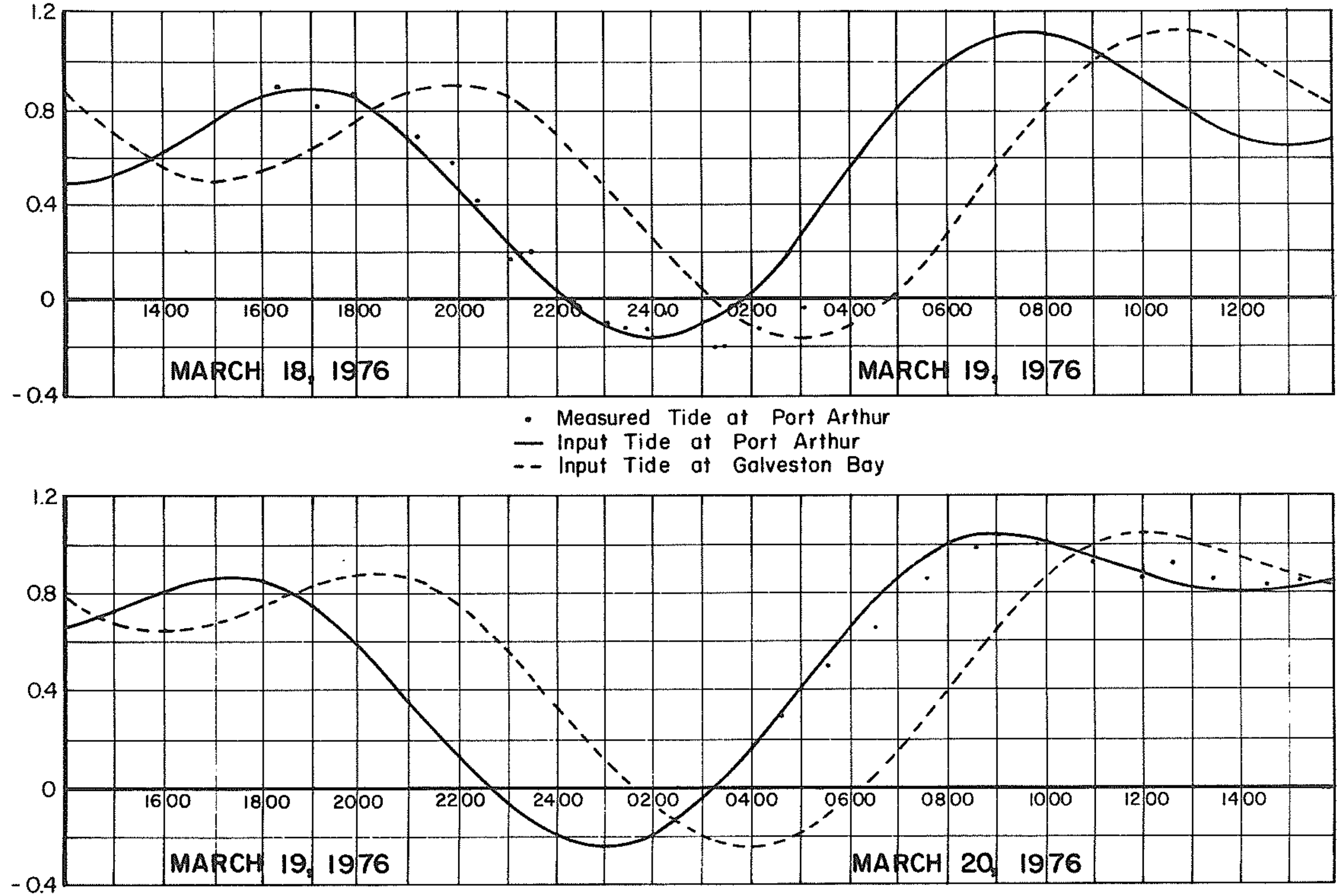


Figure 32. Tides at Galveston Bay and Port Arthur - March 18, 19 and 20, 1976.

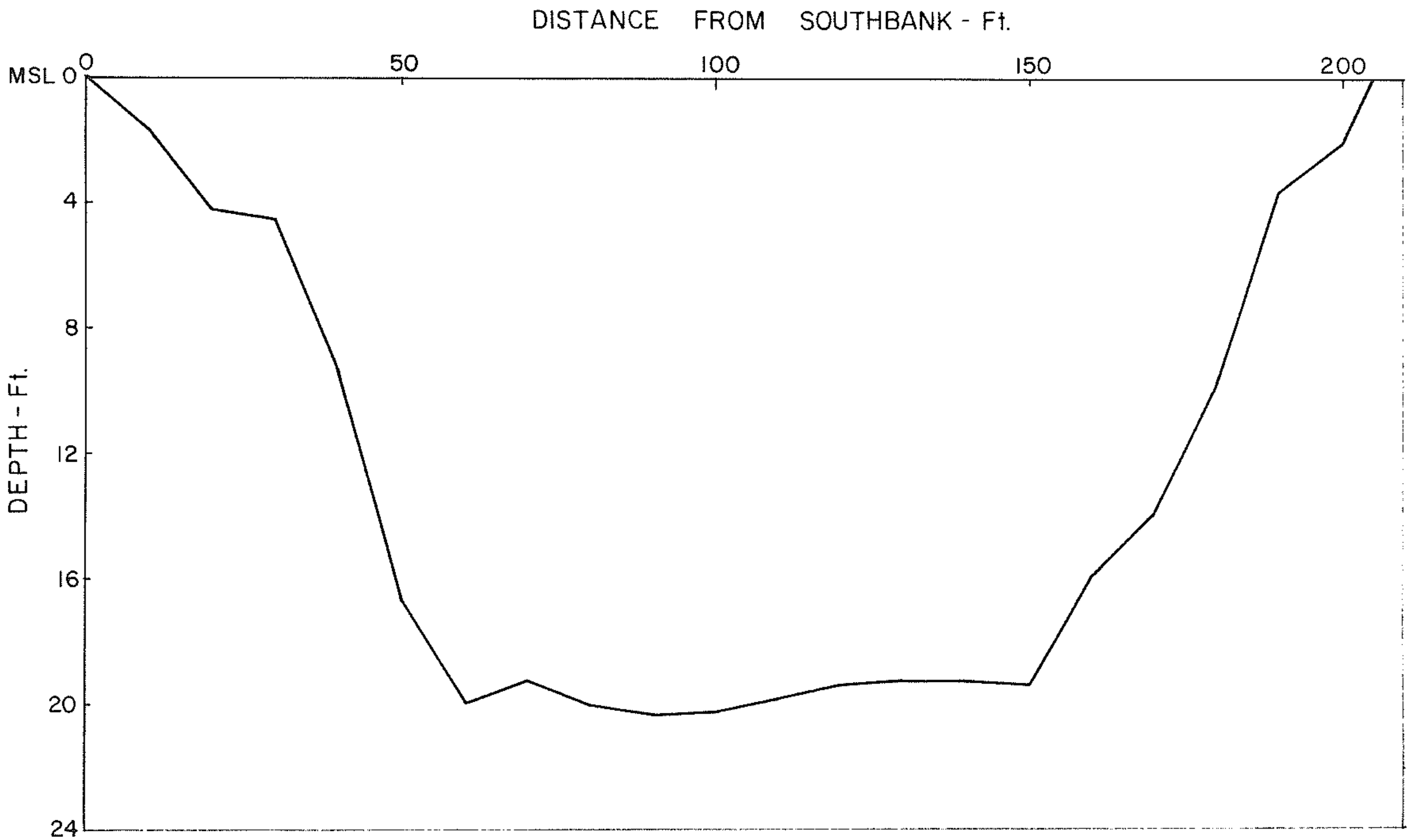


Figure 33. GIWW Cross-Section Measured at High 124 Bridge.

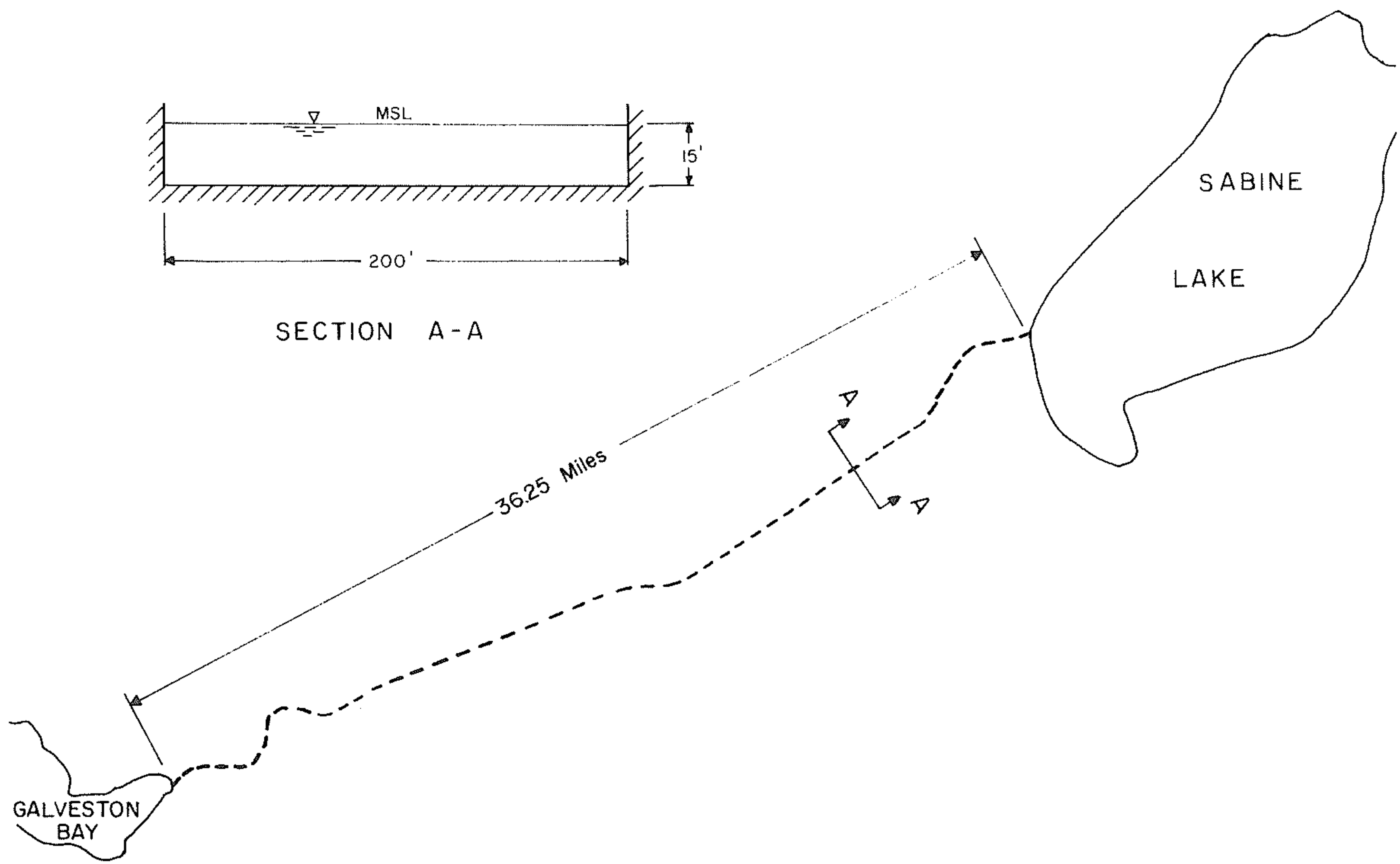


Figure 34. General Layout.

Depth, d = 15 ft (4.57 m)

Width, b = 200 ft (61.0 m)

Length, L = 36.25 miles (58.33 km)

Segment, Δx = 3.02 miles (4.86 km)

Choice of Δt

In order to obtain a stable solution in the numerical model, the following inequity has to be satisfied:

$$\Delta t < \frac{\Delta x}{\sqrt{g(d+\eta)}} \tag{4}$$

where:

Δx = length of each segment

d = depth of the canal

η = amplitude of tide

Substituting Δx = 3.02083 miles = 15,949 ft (4,861 m), g = 32.2 ft/sec^2 (9.81 m/sec^2), d = 15 ft (4.57 m), and η = 0.5 ft (0.15 m) into Eq. (4) gives

$$\Delta t < 713.9 \text{ sec}$$

Consequently t = 600 sec was selected for the numerical model.

Input Tide

The tide at both ends of the canal was determined from the tide curve shown in Figure 32 for every 600 sec for the period of March 18 through March 20, 1976, and was used as the input tide. Possible differences in water level at both ends of the canal due to wind set-up or excess freshwater inflow into Sanine Lake can be incorporated into the numerical model by raising mean sea level at Port Arthur to certain assumed values.

Choice of Manning's Coefficient

Values of Manning's coefficient (represented as n) vary from 0.020 to 0.040 in estuaries and canals (Harleman & Thatcher, 1973). For the case under consideration, the larger values for the Manning coefficient tend to decrease tidal amplitude and flow rate and to delay the time of high and low flow rate. Since a uniform cross-section of the canal was used over the entire reach, the same Manning coefficient was used over the entire reach of the canal. A comparison between the results given by the numerical model and tide and flow rate measured would determine appropriate values for the Manning coefficient.

Results

Comparison with Field Data

Throughout the field measurement period, the wind speed was about 10 knots (5.1 m/sec) and the effect of wind stress on the field measurements was considered to be negligible. Therefore, no wind was assumed in the numerical model. Four values of Manning's coefficient (0.020, 0.025, 0.030, 0.035) were tested. Values in the range of 0.0 through 1.0 ft (0.0 through 0.30 m) were used as difference in water levels at both ends of the canal (represented as D). Output data for various input conditions were compared with field data. The input data which seem to give fairly good agreement were a Manning coefficient of 0.025, mean sea level at Port Arthur 0.2 ft (0.06 m) higher than at the Galveston side of the canal and no wind. Figures 35 and 36 show output given by the numerical model for n = 0.025, D = 0.2 ft (0.06 m) and no wind conditions together with field data taken at High Island. Flow rates computed by the numerical model for the same input are in good agreement with the measured flow rates at Port Arthur (see Figure 37). Figures 38 and 39 show the case similar to Figures 35 and 36 except D = 0.0 ft.

Manning's coefficient of 0.025 seems to represent channel roughness for the GIWW, and this value will be used for later applications. The difference in mean sea level of 0.2 ft (0.06m) can easily be created by wind set-up and/or excess freshwater inflow into Sabine Lake. Since tidal fluctuation is very small (in the range of 1 ft (0.30 m)) in the GIWW, a small difference in mean sea level has a significant effect on flow rate in the canal.

Effect of Difference in Mean Sea Level

Using the tides estimated for the period of March 18 through March 20, 1976, and with the assumption of no wind conditions, various values of D were used. Mean water level in Port Arthur was always assumed to be higher than that in the Galveston side. Maximum flow rates in either direction are shown in Figure 40. Magnitude of maximum flow rate in either direction would decrease as one goes from Sabine Lake to Galveston Bay. Because of small tidal range, there is no flow reversal for D = 1.0 ft (0.30 m) and flow is always towards Galveston Bay. For D = 0.0 ft (0.00 m) flow in the same magnitude fluctuates in both directions, resulting in no net flow towards Galveston Bay.

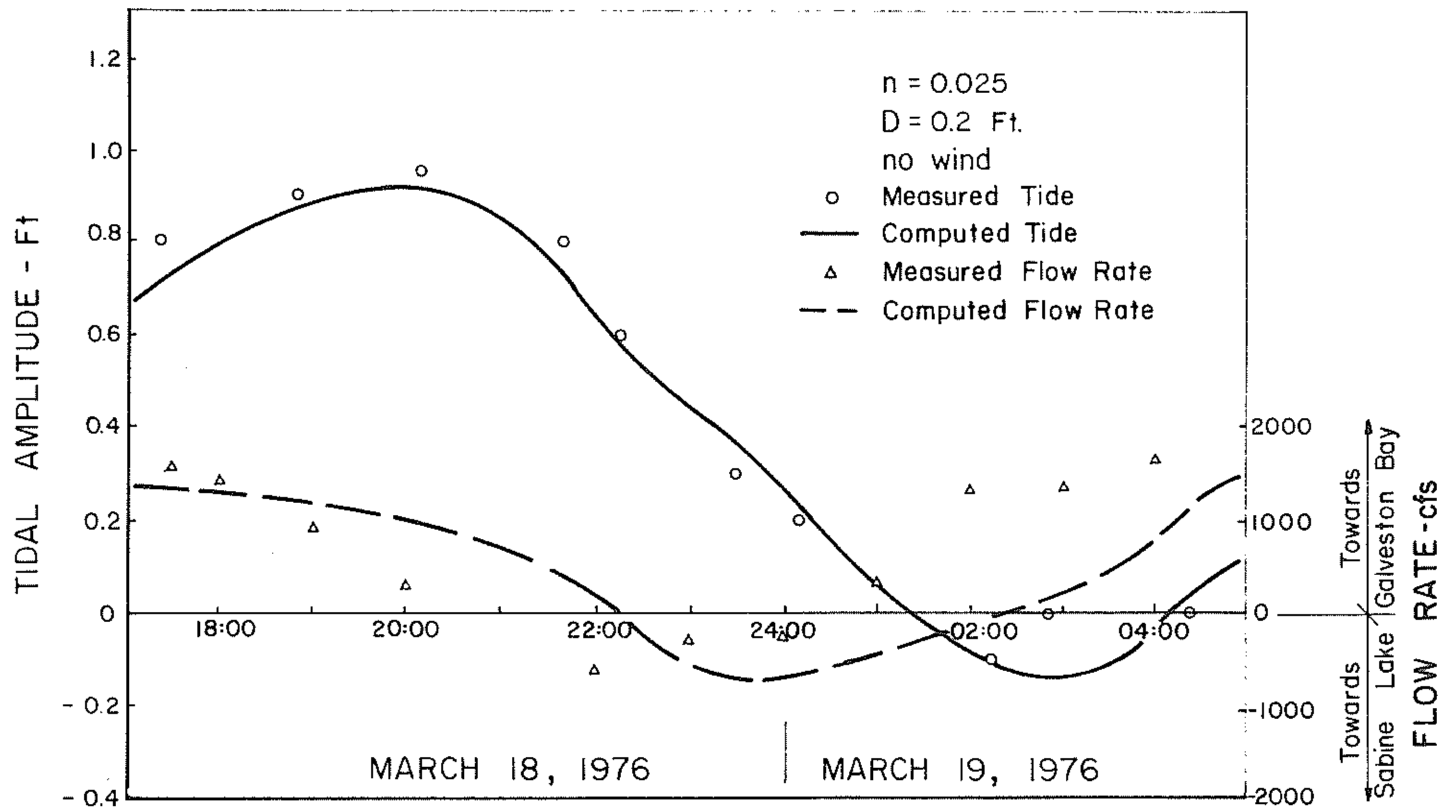


Figure 35. Tides and Flow Rates at High Island (D = 0.2 ft) - March 18 and 19, 1976.

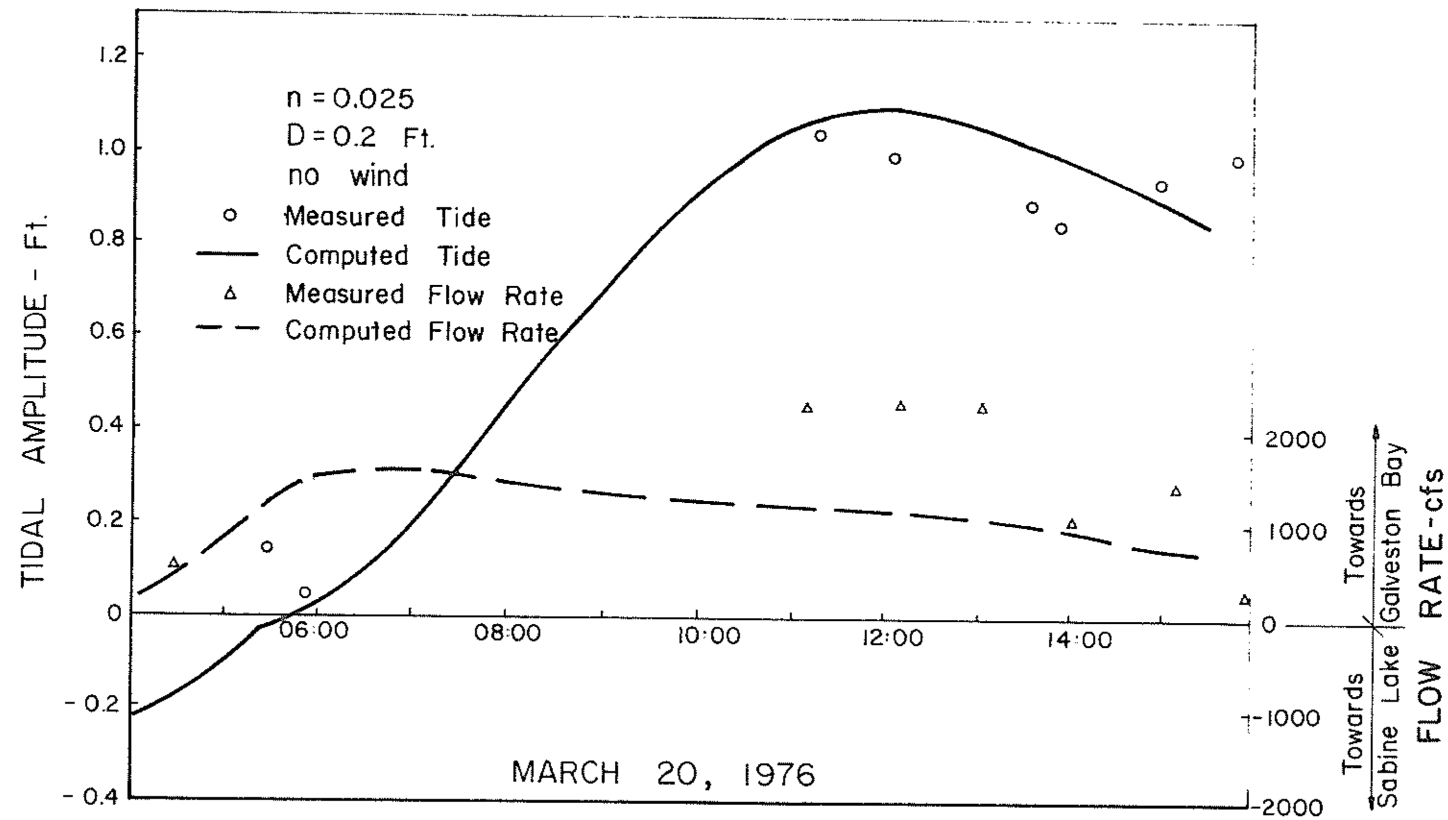


Figure 36. Tides and Flow Rates at High Island (D = 0.2 ft) - March 20, 1976.

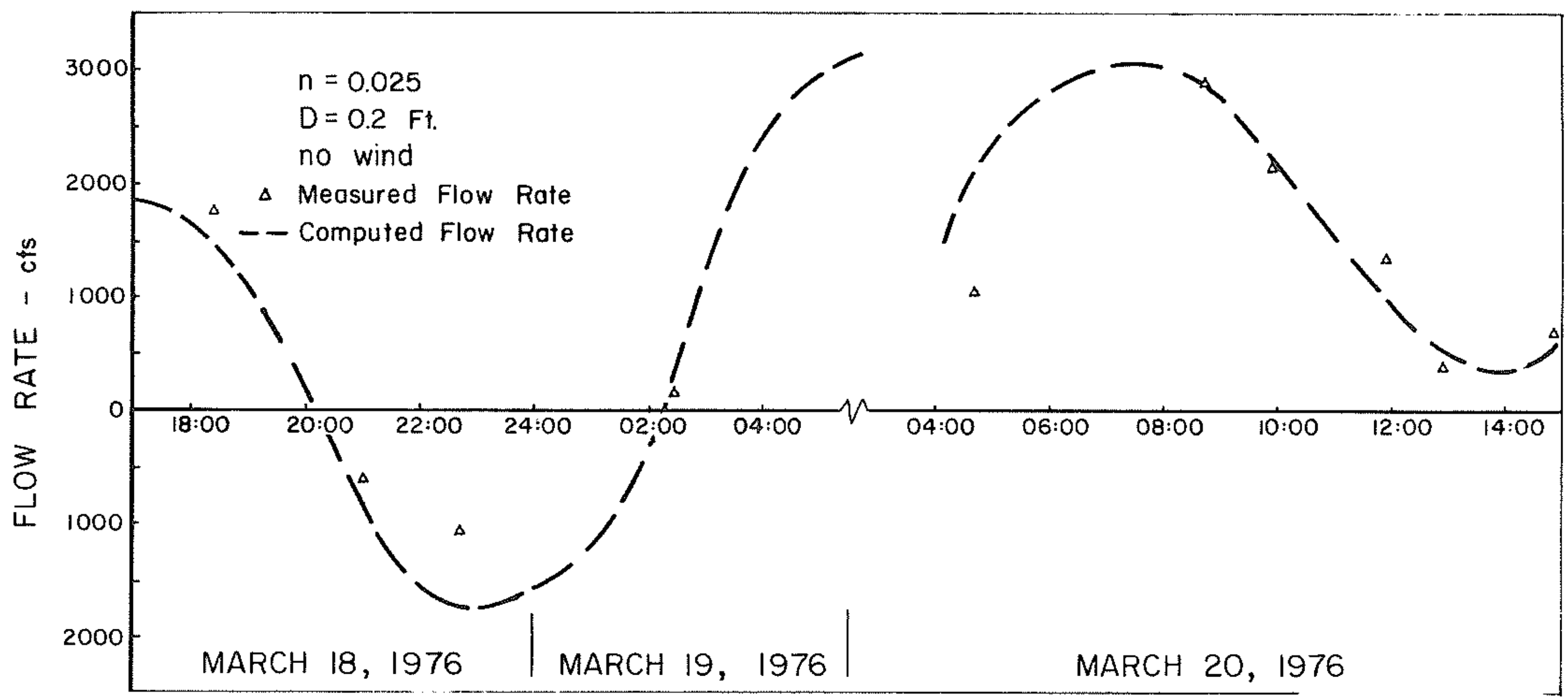


Figure 37. Measured and Computed Flow Rates at Port Arthur.

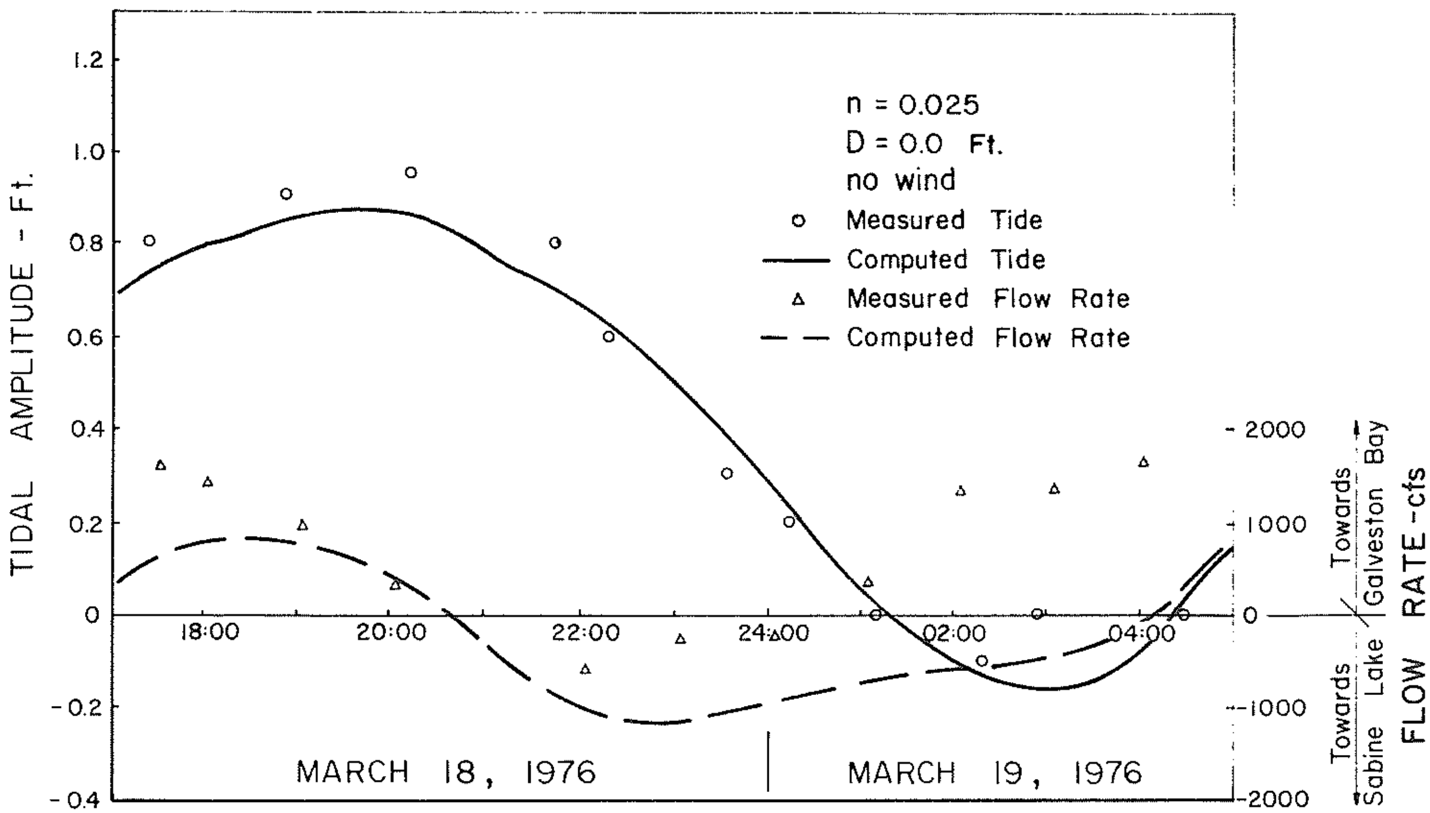


Figure 38. Tides and Flow Rates at High Island (D = 0.0 ft) - March 18 and 19, 1976.

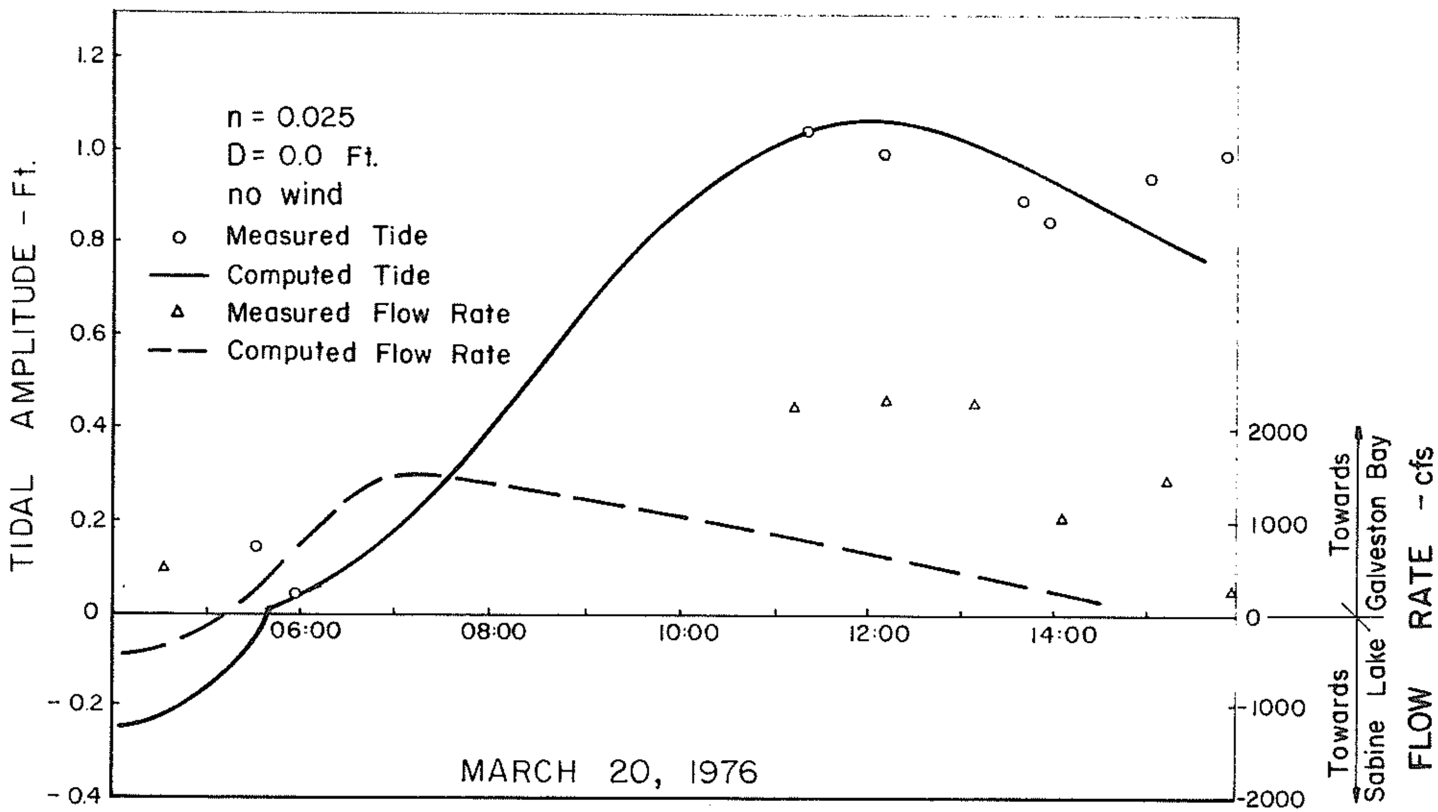


Figure 39. Tides and Flow Rates at High Island (D = 0.0 ft) - March 20, 1976.

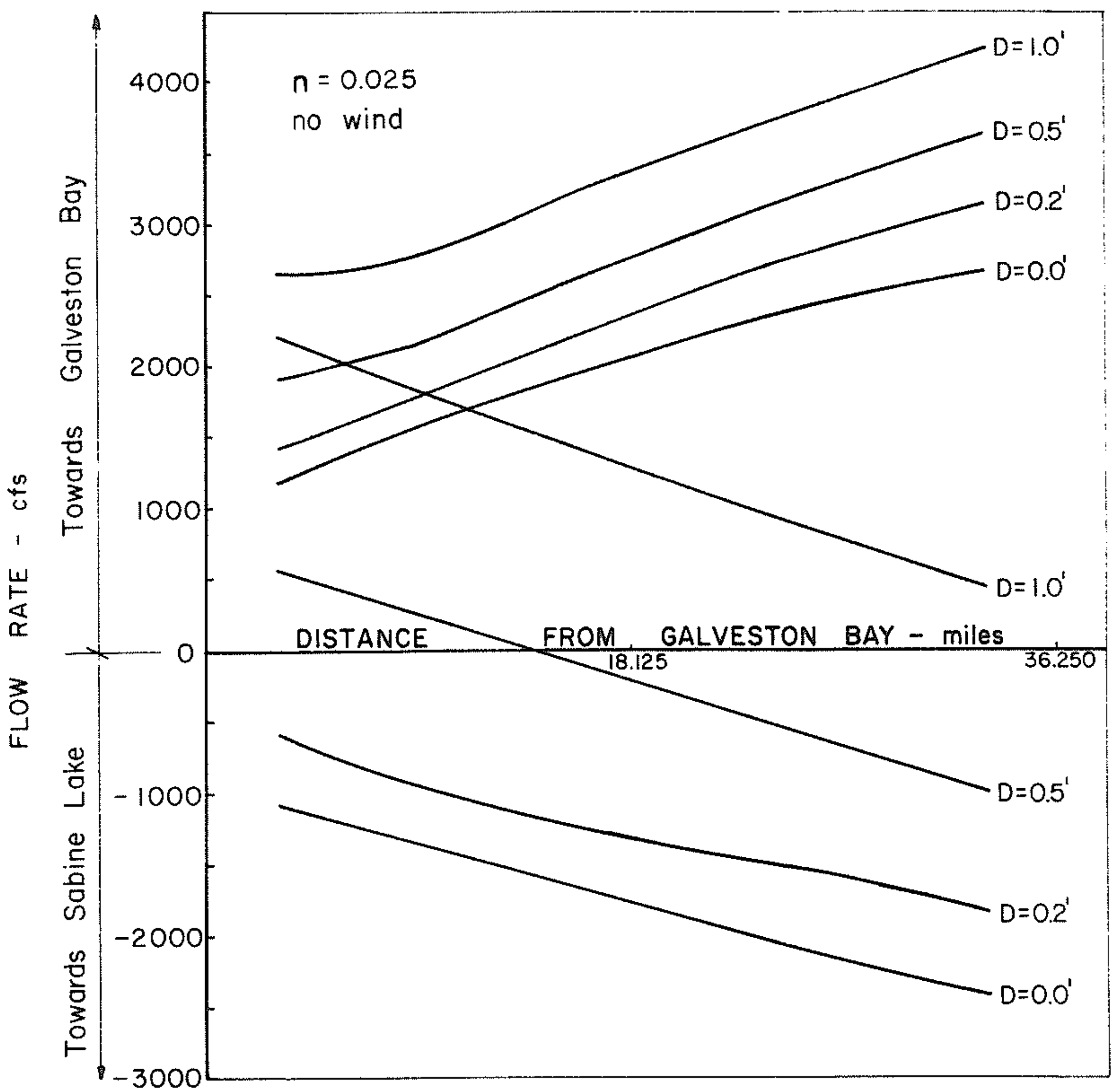


Figure 40. Effect of Differences in Water Levels on Maximum Flow Rates.

Effect of Wind Stress

It was assumed that wind is blowing from Sabine Lake towards Galveston Bay in parallel with the GIWW, and different wind speeds were tested by using the input tide used previously. Difference in mean sea level was assumed to be zero. Figure 41 gives maximum flow rate in either direction. For wind speed of 40 knots (20.6 m/sec), wind effect is not insignificant.

Summary

Manning's coefficient for the GIWW was found to be around 0.025. Wind stress on the waterway has less effect on flow rate in the GIWW than difference in mean sea level at both ends of the canal. Because of small tidal range in the GIWW, wind set-up and/or excess freshwater inflow into Sabine Lake can create significant flow towards Galveston Bay. Under normal conditions, a maximum flow rate of 4000 cfs (113.4 cms) and a maximum current velocity of 1.3 ft/sec (0.396 m/sec) can be expected.

Miscellaneous Considerations on Salinity Intrusion

Salinity intrusion in estuaries and canals has significant effect on sedimentation on the bottom and water quality. As a part of the field measurements conducted from March 18 through March 20, 1976, salinity was measured at Port Arthur (in Port Arthur Canal, Sabine-Neches Canal, and in the GIWW) and at High Island. Also, salinity measurements were carried out as a part of the 1975 field program. Based on the field data, salinity intrusion in the GIWW as well as in its neighboring canals will be discussed in this section.

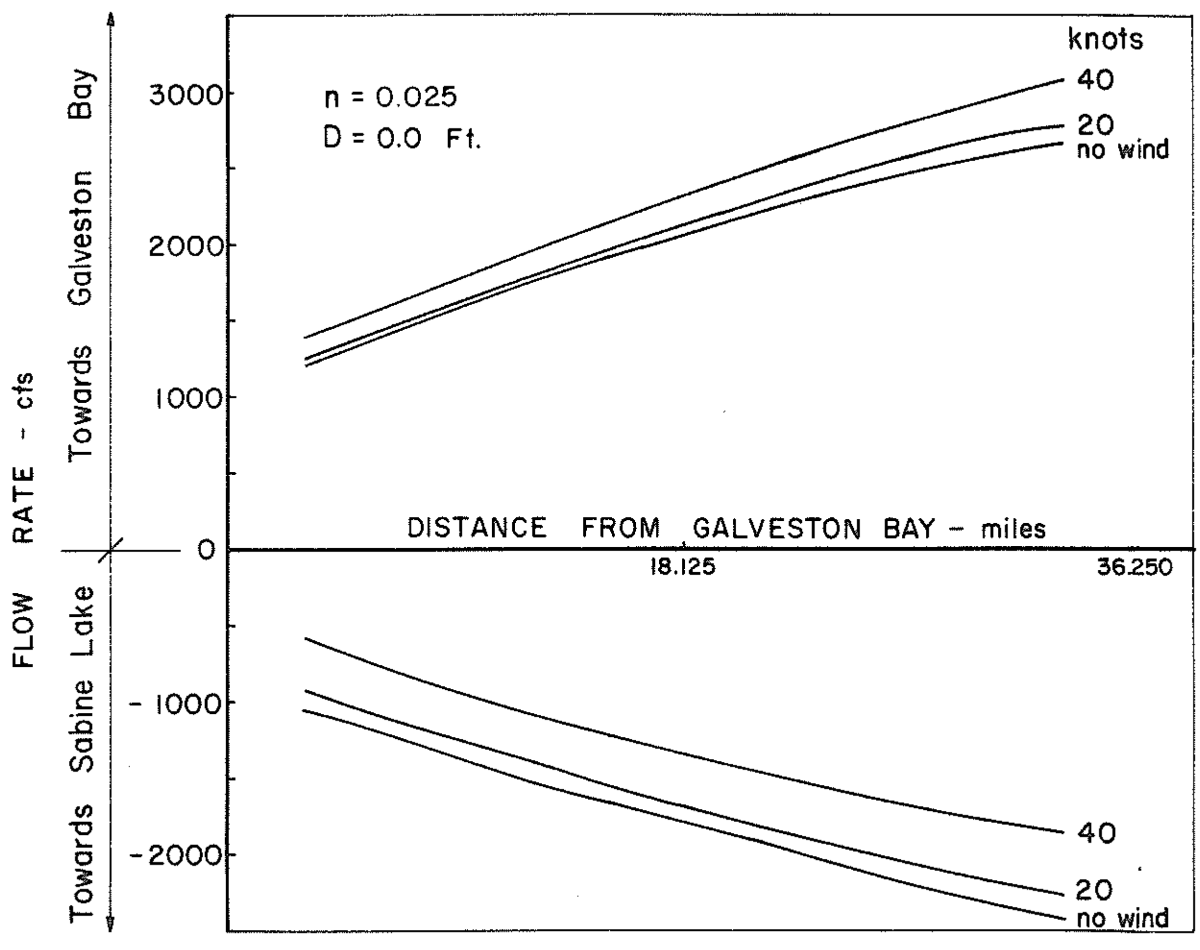


Figure 41. Effect of Wind on Maximum Flow Rates.

Salinity Intrusion in Neighboring Canals

Port Arthur Canal has a controlling depth of 40 ft (12.2 m) to Port Arthur Canal. Strong salt finger was detected near the bottom of the Port Arthur Canal as well as in Sabine-Neches Canal which has a controlling depth of 40 ft (12.2 m) from Port Arthur to upstream. During the period of the field measurements (March 1976) surface salinity ranged from 11 to 13 ppt for March 18 to 19, while bottom salinity fluctuated from 15 to 21 ppt during the peak of flood tide. On March 20, surface salinity ranged from 6 to 9 ppt while bottom salinity varied from 10.5 to 18.6 ppt. Strong surface currents of 1.25 knots (0.64 m/sec) flowing towards Sabine Pass were observed in the beginning of flood tide while bottom currents started to go upstream in the canals.

Salinity Intrusion in GIWW

Since neighboring canals have a controlling depth of 40 ft (12.2 m) compared to a depth of 12 ft (3.7 m) in the GIWW, the less saline water flowing near the surface of Sabine-Neches Canal is believed to flow into the GIWW and a salt finger generally does not go into the GIWW.

At the Galveston side of the GIWW, surrounding area is shallower than the GIWW, so a weak salt finger, if present, can extend into the GIWW. During the field measurements conducted in 1975, a weak stratification characteristic of salinity was detected in the GIWW near Galveston Bay, while the rest of the reach had almost uniform salinity from the surface to the bottom.

Circulation Study of Lower Laguna Madre

Circulation patterns in estuaries and bays have significant effect on sediment transport. The large shoaling rate in canals and waterways has direct bearing on economic efficiency of the canals and waterways. The Gulf Intracoastal Waterway (GIWW) crosses many estuaries and bays along the Texas coast, and some of the reaches where the GIWW crosses estuaries and bays are known to have high shoaling rates. Circulation in the region adjacent to the waterway has significant effect on shoaling rates in the waterway. Using statistical data of dredging in the GIWW, shoaling characteristics of the GIWW in Texas were analyzed (Atturio, et al., 1976), and those reaches where high shoaling rates exist were identified. In Lower Laguna Madre between miles 657 and 660, a significantly high shoaling rate was noted (an average shoaling rate of 2.7 ft/year (0.82 m/year) was computed) (see Figure 42). The only available current measurements in this region were by Denison and Henderson (1956), and understanding of currents in this region is still in the stage of speculation. In this study it was attempted to analyze circulation patterns in this part of Lower Laguna Madre using satellite imagery. The Lower Laguna Madre is separated from the Upper Laguna Madre by land-cut area. There are only two inlets connecting this area directly to the Gulf. One is the Port Mansfield Channel which has a jettied entrance channel of 26 feet (7.92 m) deep and 250 feet (76.2 m) wide. Another inlet is Brazos Santiago Pass which has a depth of 38 feet (11.58 m) and a width of 300 feet (91.48 m).

The GIWW runs through the land-cut area, and continues to follow the Laguna Madre between Padre Island and the mainland. The Lower Laguna

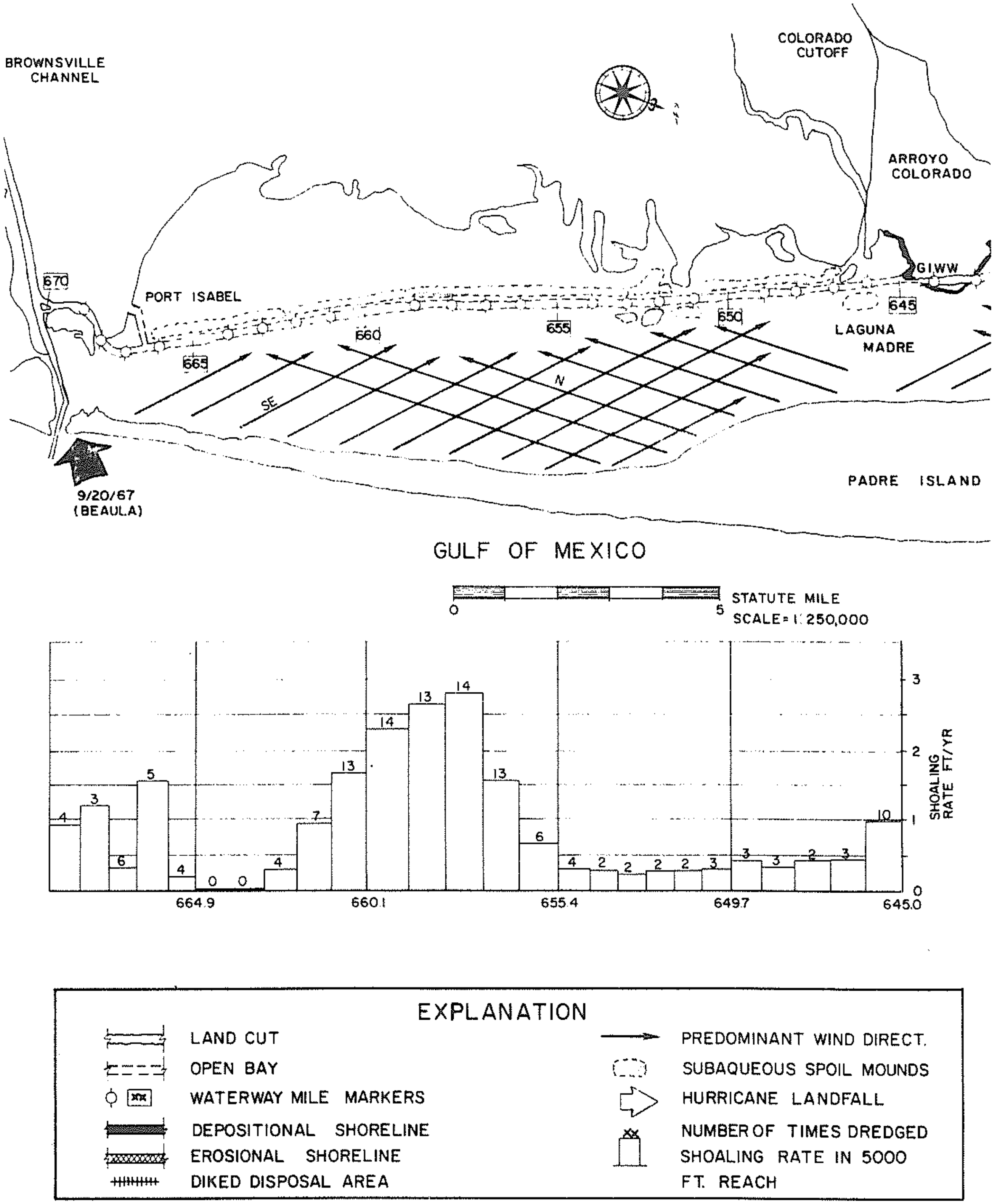


Figure 42. Shoaling Rate in GIWW in the Southern Part of Lower Laguna Madre (from Atturio, et al., 1976).

Madre prior to construction of the GIWW and Port Mansfield channel was an inaccessible hypersaline shallow estuary due to restricted water circulation, very little freshwater inflow, and high rates of evaporation. Under ordinary conditions the mean tidal range is about 1.5 feet (0.46 m) and the extreme range is about 2 feet (0.61 m) at the Gulf entrance, about 1.5 ft (0.46 m) at Port Isabel. During strong "northers" in the winter season the water surface in the southern end of the Lower Laguna Madre may be raised 4 feet (1.22 m) or more above the mean low tide in the Gulf. Hurricanes in summer and fall months have caused tide heights as much as 12 feet (3.66 m) above mean low tide at Port Isabel.

The completion of the Port Mansfield Pass had a strong effect in water circulation in the estuary. During the prevailing southeast wind, the water enters the Brazos Santiago Pass through a minimum cross-section of 43,200 square feet (4,013 square meters). Water leaves the estuary through a land cut with a minimum cross-section of 3,600 square feet (334 square meters) and Port Mansfield Pass provides an outlet for the water built up in the northern part of the Lower Laguna Madre where the current flows out of the estuary into the Gulf.

Since the completion of the Port Mansfield Pass in 1957, several notable changes occurred in the ecology of the estuary area. The number of juvenile red fish inhabiting the estuary has substantially increased. Juvenile brown shrimp populations extended their range from south of Port Mansfield to nearly all of the northern section of the Lower Laguna Madre, a vast area previously of very low productivity. Landings of flounder by both sport and commercial fishermen have increased manyfold since the opening of the pass. It has also been noted from trawl samples that juvenile trout have been found in abundance in the established grass beds which have increased in stand since the opening of the pass. Vegetation, including shoal and widgeongrass, has increased both in range and in stand.

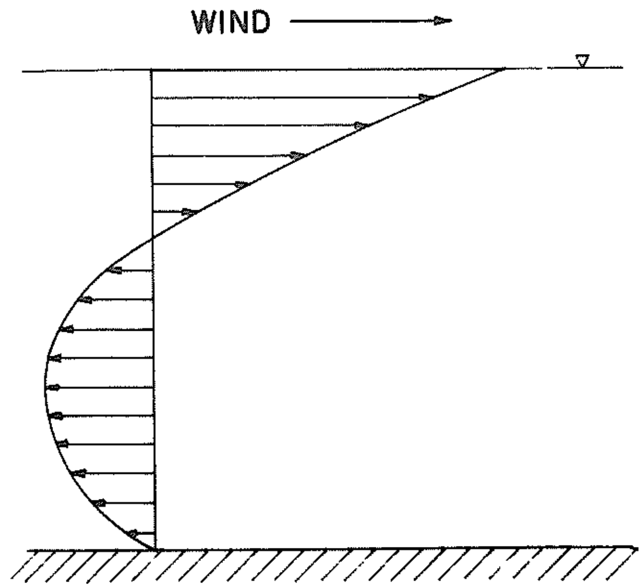
Photographs taken from satellite orbiting the earth have been used in studying estuarine circulation in recent years (for example, the work done by Klemas, et al., 1974).

Two LANDSAT (previously called the Earth Resources Technology Satellite, ERTS) satellites are at present orbiting the earth. LANDSAT imagery has been available since 1972, and the repetitive and seasonal coverage provided by LANDSAT imagery is an important tool for the interpretation of the dynamic estuarine and coastal processes. LANDSAT imagery is especially useful in identifying near-surface currents, and is considered to be useful in studying circulation patterns in the shallow region under consideration. LANDSAT imagery in both bands 5 and 7 was obtained from EROS Data Center in Sioux Falls, South Dakota for every month of the year (total circulation patterns for different wind and tide condition. Imagery in band 5 was used in identifying suspended sediment patterns, and imagery in band 7 was utilized in delineating land-water boundaries. Six frames of the imagery were considered representative and are presented in this report. All of the LANDSAT imagery was taken around 10 am, local standard time. Wind data at 9 am at nearby Brownsville was available from the Weather Bureau. Tidal range at Brazos Santiago Pass is relatively small in the range of 1.4 feet (0.43 m) for diurnal tide. However, the region under consideration is very shallow resulting in relatively strong tidal currents. Some tidal effects on currents in this region were detected by Denison and Henderson (1956). As one travels north, the effect of tides on currents becomes less noticeable.

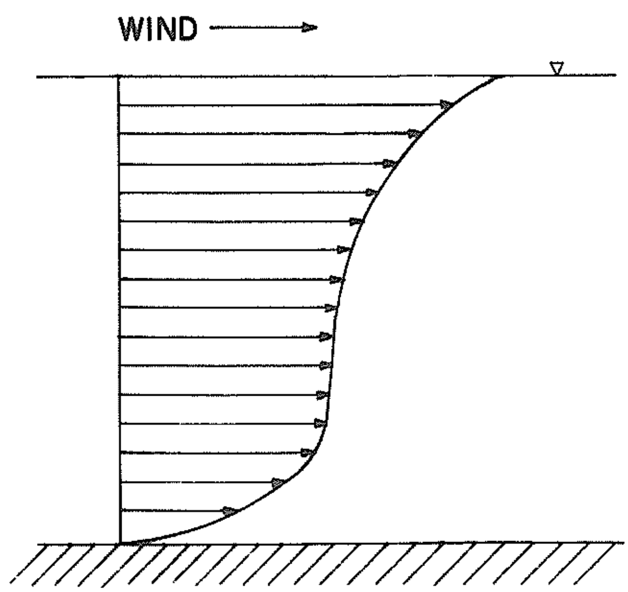
In Lower Laguna Madre, water depths adjacent to the GIWW are very shallow, seldom exceeding 3 feet (0.9 m) while the waterway is 12 feet (3.66 m) deep and 125 feet (38.1 m) wide. Freshwater inflow in Lower Laguna Madre is negligible and water is well mixed. An estuary with this shallow depth and negligible freshwater inflow can be considered to be a single-layered estuary. For a single-layered estuary, stratification effects due to salinity differences can be neglected.

Wind blowing over estuaries of single layer will cause surface currents flowing in the direction of the wind. Estuaries can also have a bottom current flowing in the opposite direction of the wind as a return flow, resulting in a zero net discharge over the total depth (see Figure 43(a)). The current can be in the same direction from the surface to the bottom, causing a net discharge in the direction of the wind (see Figure 43(b)) (Reid, 1957). The region under consideration is believed to be influenced by wind, tide and depth, and the relationship between surface currents and bottom currents varies. Moreover, due to its shallowness, surface waves have significant effects on net discharge over total depth. However, in this study it was assumed that water movements near the surface are indicative of overall water movements, and eventually the overall movements of suspended sediments.

Turbidity of the waters of the Lower Laguna Madre was analyzed previously (Breuer, 1962), and varied considerably depending on the wind, current, tide, water runoff, depth of water, and bottom type. The most important factor was the presence or abundance of bottom vegetation. Water



(a) Vertical Velocity Profile With Return Flow Near the Bottom.



(b) Vertical Velocity Profile Without Return Flow Near the Bottom.

Figure 43. Current Profile in Estuaries With and Without Return Flow.

overlying a bottom devoid of vegetation was seldom clear, and a bottom with heavy growth of submerged vegetation was seldom turbid. Turbidity was greater in waters over a silt or clay bottom, and less over a sand bottom.

Water in this region is always quite turbid, and wind-driven currents near the surface in the region under consideration can be identified by studying the suspended sediment pattern on LANDSAT imagery. Circulation patterns identified on LANDSAT imagery were correlated to wind and tide data, and they are presented here for each of the six images used. Tidal information shown in the following figures was taken from the predicted tide tables of the National Ocean Survey.

January 21, 1973 Imagery

Suspended sediment plume on the imagery obviously suggests that there is a flow crossing across the waterway around mile 660. Tide at Brazos Santiago Pass is near low tide, and water level in this region is going down. Water seems to be flowing toward the Brazos Santiago Pass responding to the tide and crosses the waterway near Port Isabel. This corresponds to the reach where relatively high shoaling rates were identified by Atturio, et al., (1976)(see Figure 44 and 45b).
The area with turbid waters has a silty bottom, and the area with clear waters along Padre Island has a sandy bottom (Breuer, 1962). Differences in bottom material explain differences in turbidity. Since turbidity was used as a tracer of currents, currents in clear water could not be analyzed in this study.

February 25, 1975 Imagery

The tide is coming in from the Brazos Santiago Pass, and flow seems to cross the waterway near Port Isabel and again somewhere between miles 657 and 660. This corresponds to the south wind blowing over the estuary (see Figures 46 and 47).

May 26, 1973 Imagery

This imagery is similar to February 25, 1975 imagery. Flow corresponds to incoming tide from the Pass and the south wind (see Figures 48 and 49).

June 8, 1974 Imagery

This is somewhat similar to February and May imagery. However, the south wind is quite strong (22 knots), causing turbid water heavily laden with suspended sediments (see Figures 50 and 51).

September 7, 1974 Imagery

This imagery is similar to January 21, 1973 imagery. The tide is going out from the Pass and wind blowing from the north (see Figures 52 and 53).

November 10, 1972 Imagery

The wind is coming from 30° with a speed of 16 knots, with the tide going out from the Pass. Again, flow crosses the waterway at two locations where a high shoaling rate was identified previously (see Figures 54 and 55).

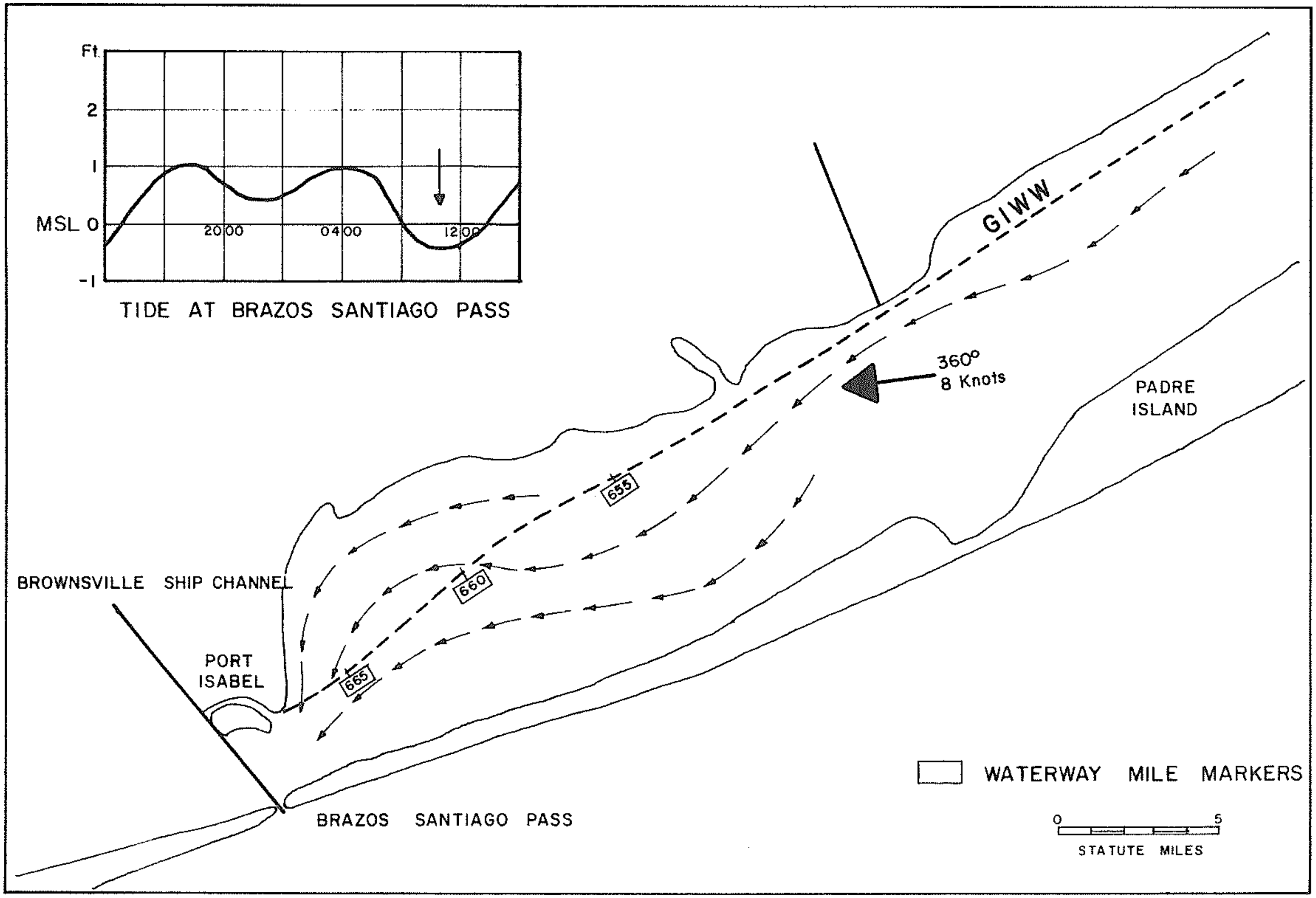


Figure 44. Flow Patterns Lower Laguna Madre - January 21, 1973.

Figure 45. Landsat Imagery - January 21, 1973.

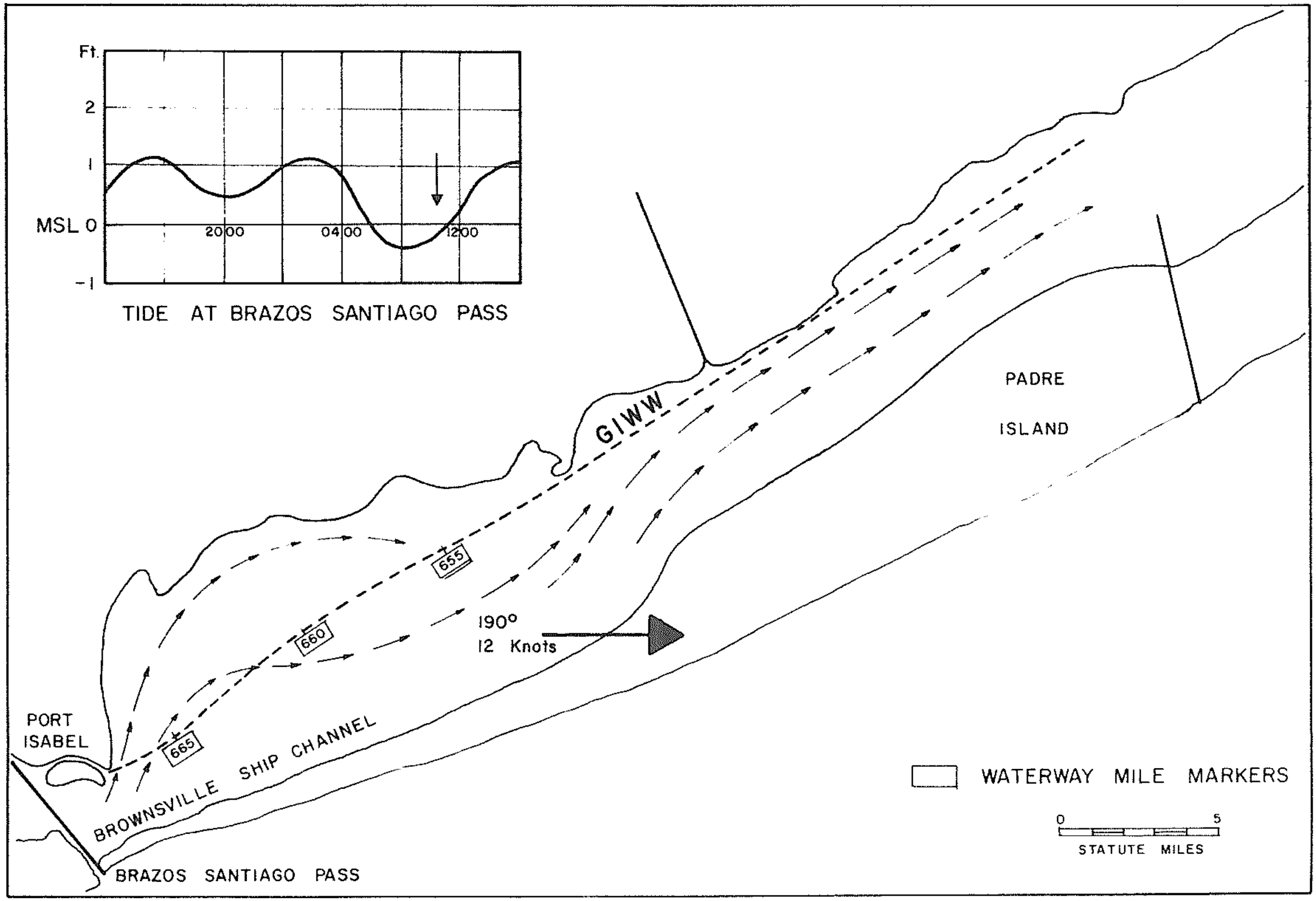


Figure 46. Flow Patterns Lower Laguna Madre - February 25, 1975.

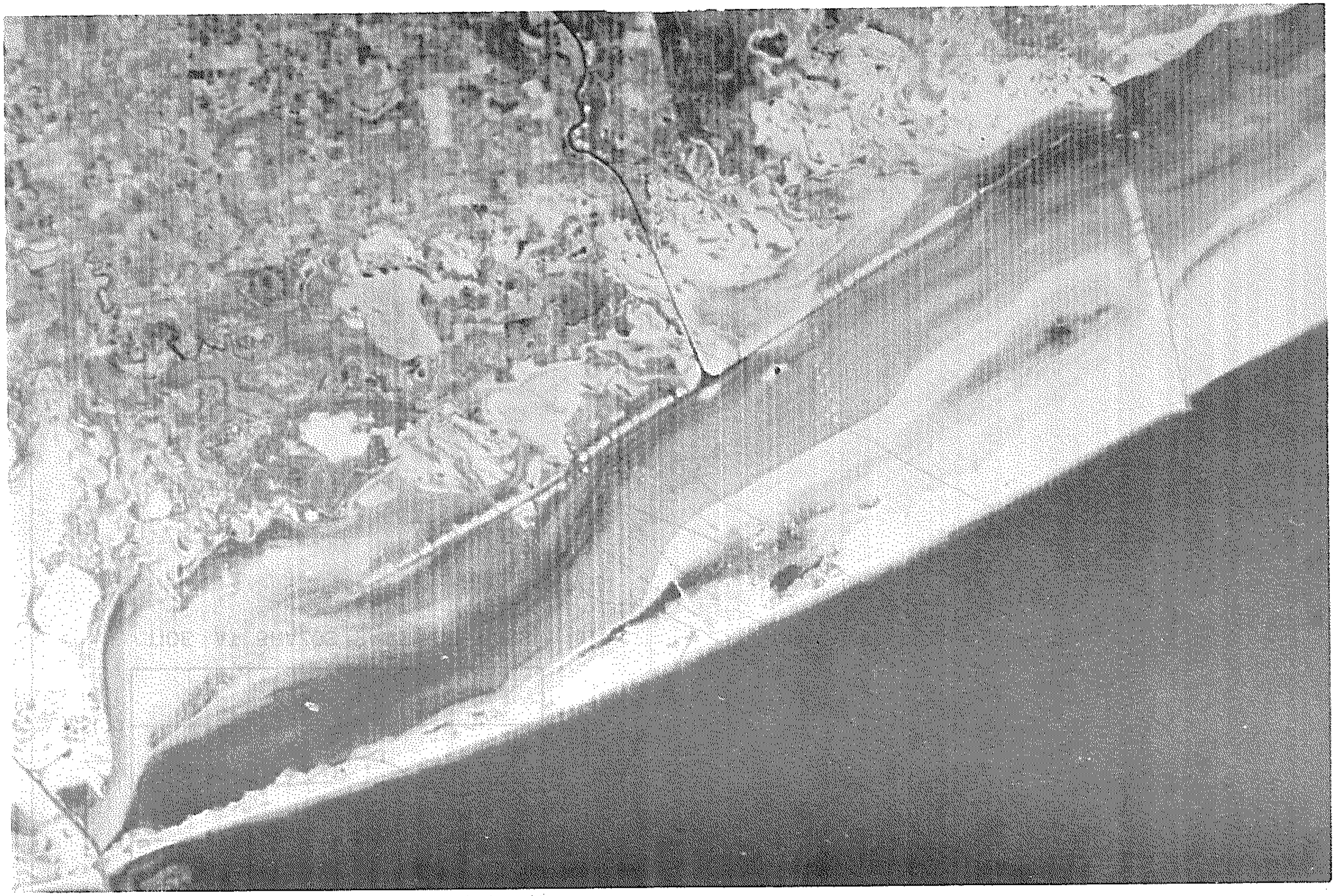


Figure 47. Landsat Imagery - February 25, 1975.

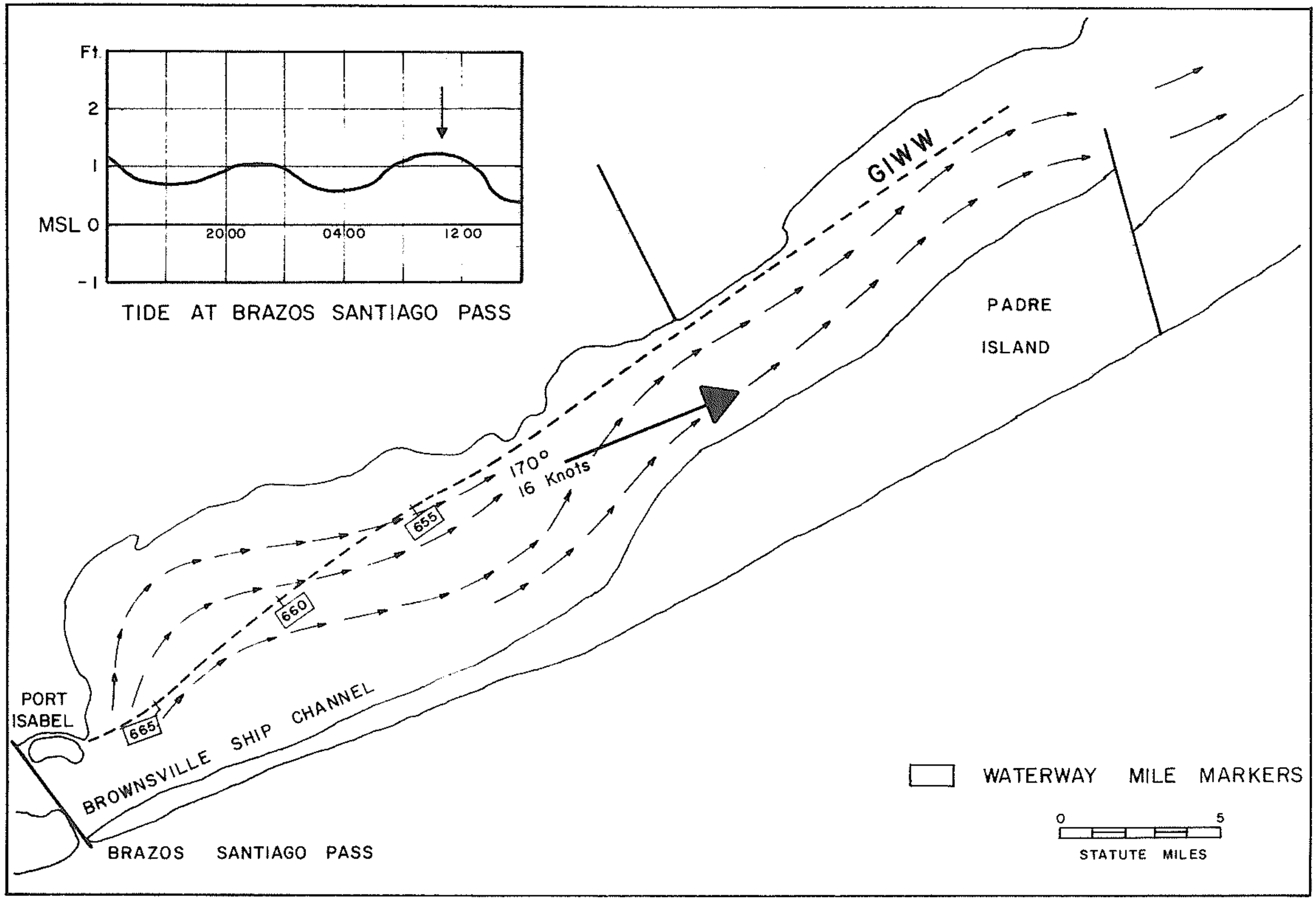


Figure 48. Flow Patterns Lower Laguna Madre - May 26, 1973.

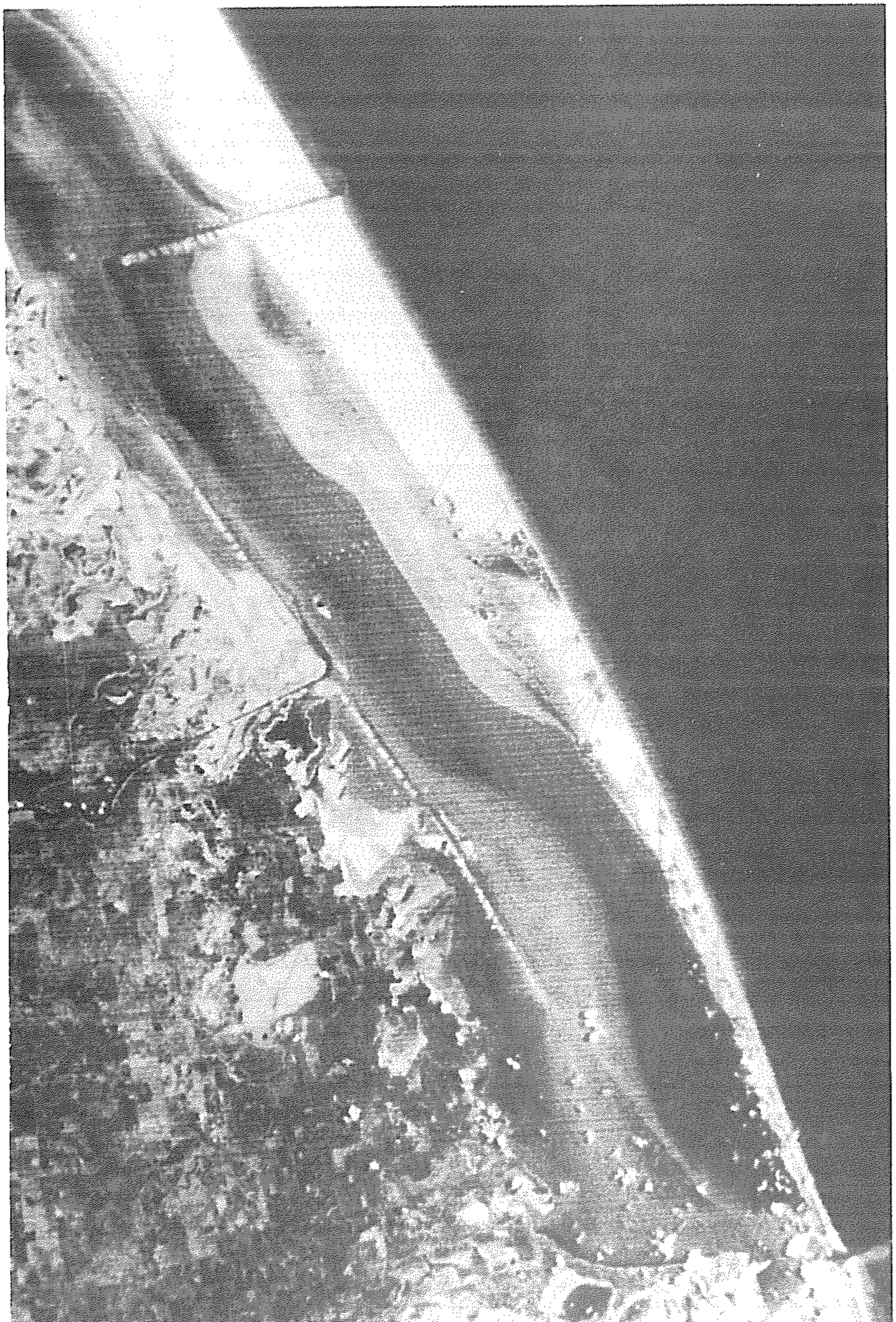


Figure 49. Landsat Imagery - May 26, 1973.

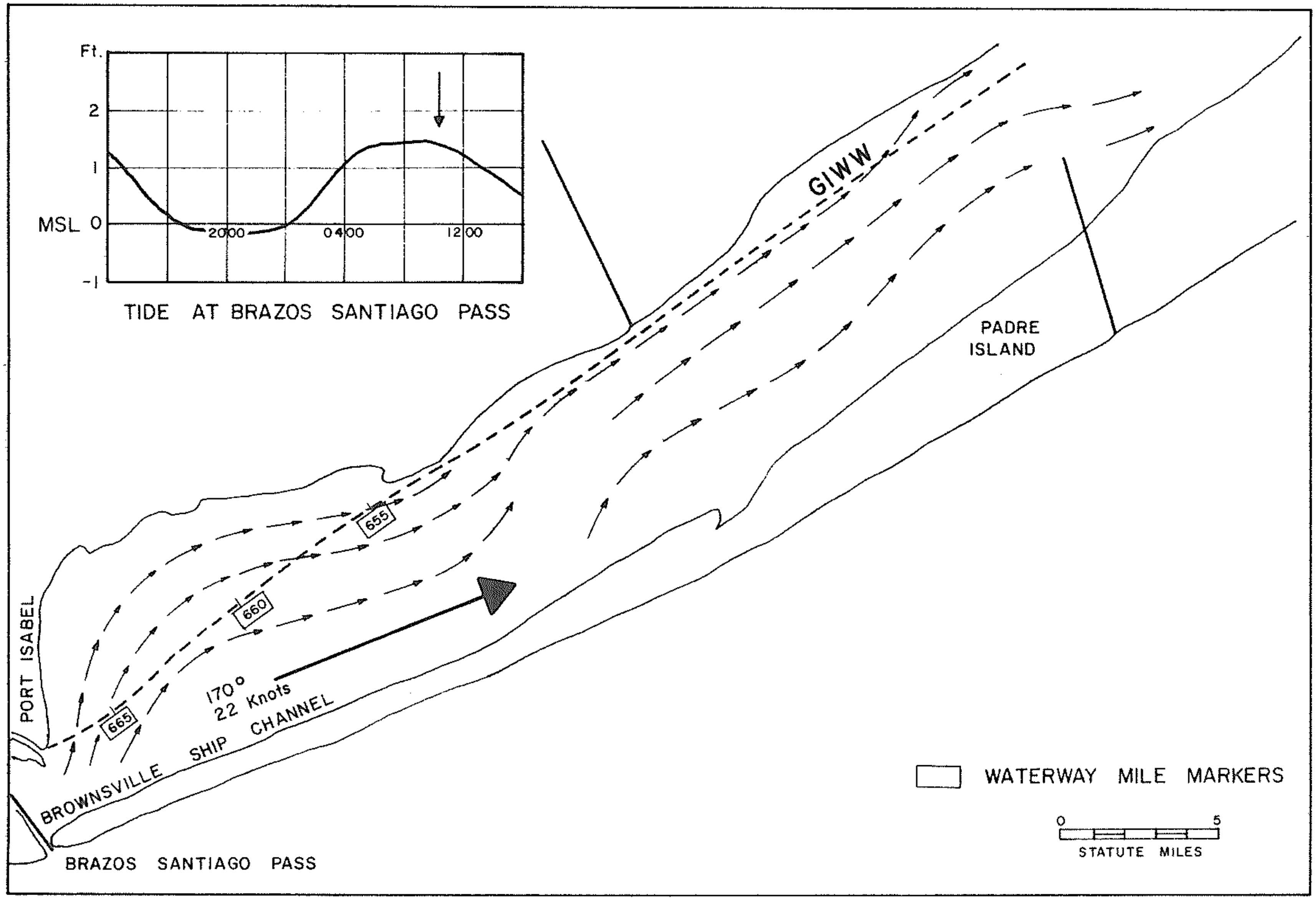


Figure 50. Flow Patterns Lower Laguna Madre - June 8, 1974.

Figure 51. Landsat Imagery - June 8, 1974.

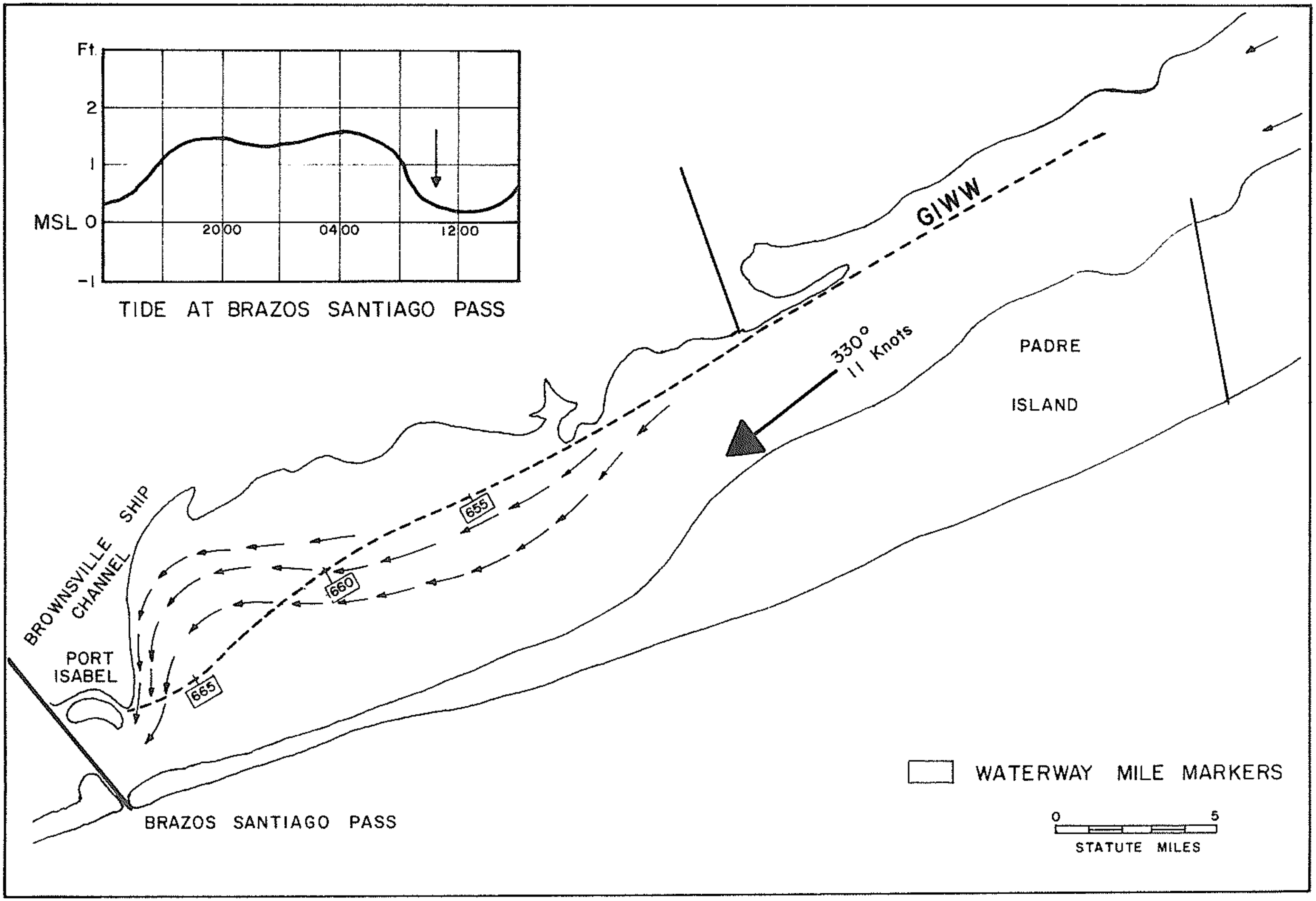


Figure 52. Flow Patterns Lower Laguna Madre - September 7, 1974.

Figure 53. Landsat Imagery - September 7, 1974.

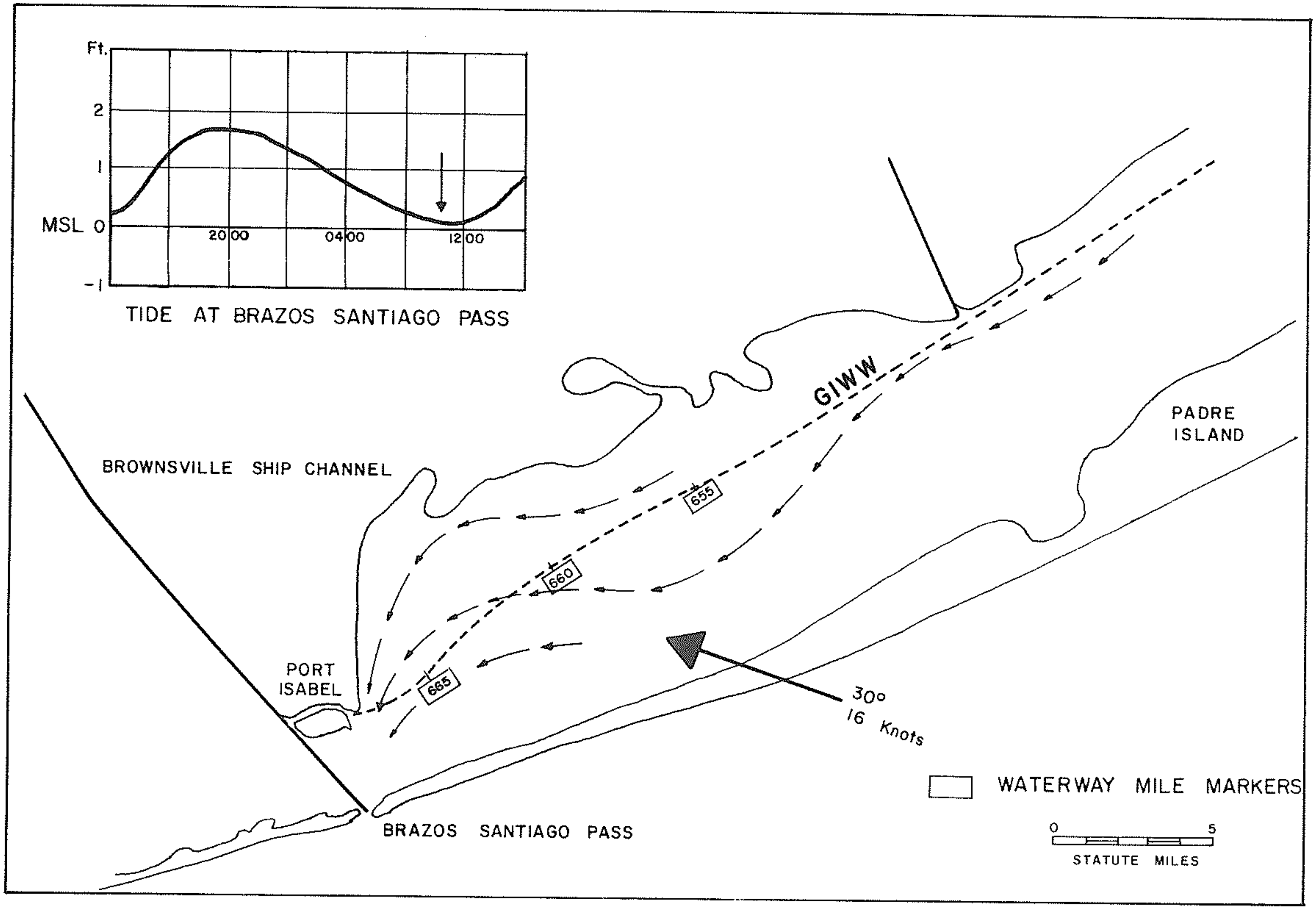


Figure 54. Flow Patterns Lower Laguna Madre - November 10, 1972.

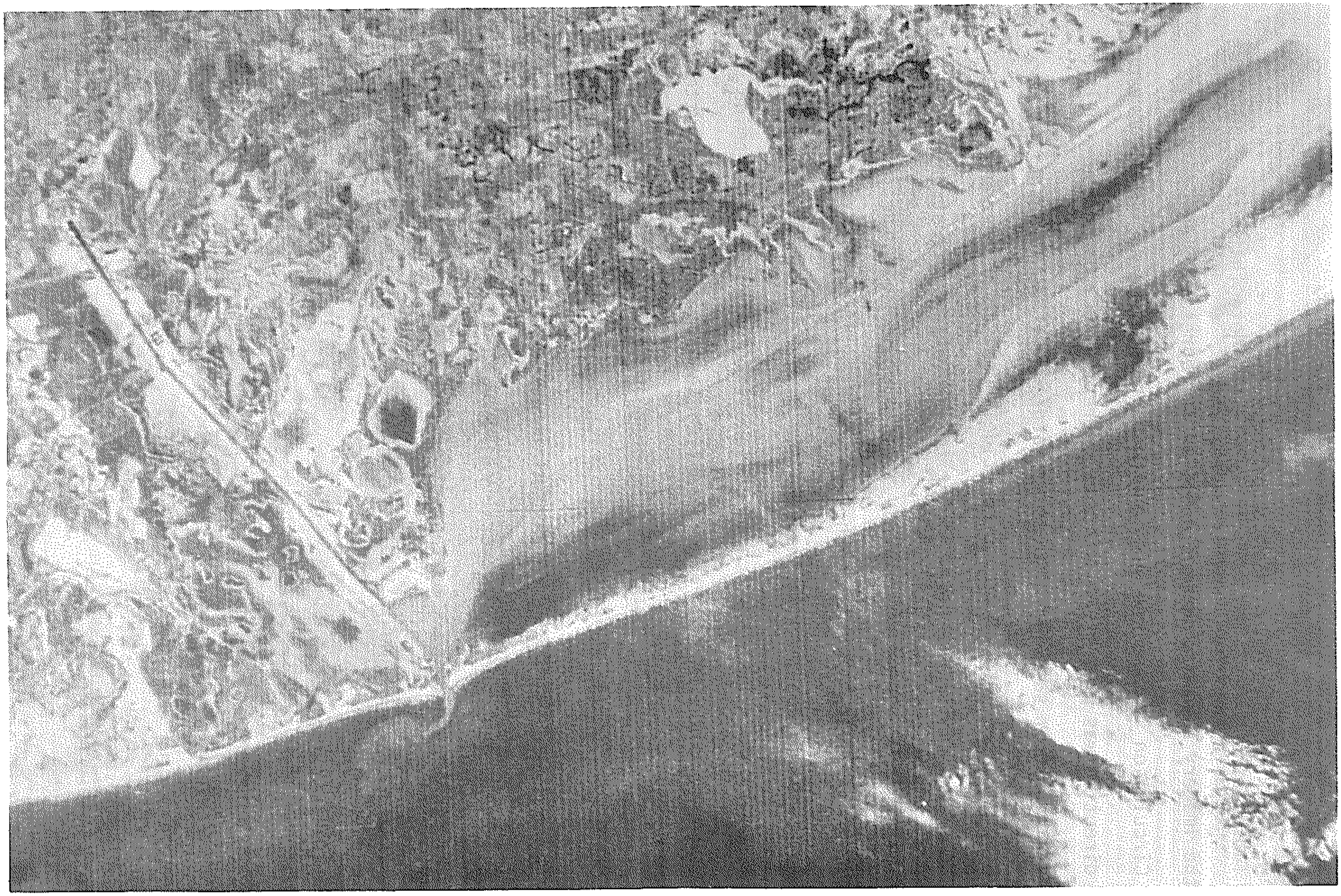


Figure 55. Landsat Imagery - November 10, 1972.

Summary

Table 7 shows wind data for Brownsville. Note that wind conditions for the imagery used can be considered to be representative.

Circulation in this region seems to be responsive to tides; however, wind direction was generally the same as current direction and no conclusion can be drawn only from satellite imagery regarding whether this shallow region is affected more by wind or by tide. Denison and Henderson (1956) found that the shallow region adjacent to the waterway is strongly affected by wind, while the waterway is affected more by the tide. Considering the very shallow depth in the region, it seems that the shallow region adjacent to the waterway is mainly wind-driven except the reach near Port Isabel which is obviously affected by tide coming from Brazos Santiago Pass at every tidal cycle. In the study conducted by Atturio, et al., (1976), an area of no dredging was noted near Port Isabel from mile 663 to mile 665. This is the reach where there is no flow crossing the waterway identified on LANDSAT imagery.

Near mile 660, there was generally always a flow crossing the waterway. Waves generated by wind have an important effect in stirring up the bottom, and the stirred-up sediments would be transported by wind-driven currents.

Table 7. Monthly Average Wind Speed and Direction at Brownsville.

Month	Mean Speed (knots)	Prevailing Direction
January	11.8	SSE
February	12.5	SSE
March	13.7	SE
April	14.4	SE
May	13.8	SE
June	12.7	SE
July	11.8	SE
August	10.8	SE
September	9.8	SE
October	9.8	SE
November	10.9	SSE
December	11.0	NNW
YEAR	11.9	SE

From: "Environmental Guide for the U.S. Gulf Coast", NOAA, Environmental Data Service, National Climatic Center, Asheville, N.C., November 1972.

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CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The purpose of this study was to identify potentially adverse environmental factors associated with the operation and maintenance of the Texas Gulf Intracoastal Waterway and to develop recommendations for implementation by the various entities concerned with the waterway. The environmental effects of dredging were not included in this study as the Corps of Engineers is conducting a major effort in this area. The following conclusions and recommendations were developed.

1. The Texas Gulf Intracoastal Waterway provides transportation connecting links between the various bays and river basins.

The Texas section of the waterway begins at the Sabine River and parallels the coast for 424 miles (682 km). The waterway traverses bays or follows land cuts for the entire length. It crosses the Sabine and Neches Rivers, traverses Galveston Bay, intersects the Brazos, San Bernard and Colorado Rivers, extends across the lower part of Matagorda, San Antonio, Aransas and Corpus Christi Bays and continues through Upper and Lower Laguna Madre to the Brownsville Ship Channel.

2. The Intracoastal Waterway can transport water, pollutants, aquatic plants and animals from one river system to another.

A one-dimensional hydrodynamic model was applied to the Sabine-Galveston Waterway system to evaluate the various factors affecting the flow of water between the two bays. Wind set-up in the bays and/or excess freshwater inflow into Sabine Lake can create a significant flow from Sabine Lake to Galveston Bay. Under normal conditions, a maximum flow rate of

4000 cfs (114 cms) and a maximum current of 1.3 ft/sec (0.396 m/sec) can be expected. The movement of water in this reach could become significant in the event of an accidental discharge of a hazardous material or the outbreak of a waterborne disease.

During the summer cruise in 1975, water hyacinth was growing along the shoreline of the reach from Sabine to Galveston and in one instance, the plant had extended across the entire width of the canal. The methods of travel for hyacinth included floating along with the currents and being carried by barge traffic.

It is recommended that a study be conducted to investigate the feasibility of constructing control facility in the reach between Sabine Lake and Galveston to limit flows and to contain hazardous materials in the event of an accidental discharge.

3. The waterway and normal operational activities in the waterway did not appear to be the major source of pollutants but elevated concentrations of nutrients and metals were usually associated with freshwater inflows.

The Neches River, Brazos River, Colorado River, Caney Creek, and Arroyo Colorado intersect the waterway and appeared to be significant sources of nutrients and heavy metals. These compounds probably enter the rivers upstream of the waterway through surface runoff and municipal and industrial discharges.

It is recommended that additional field studies be conducted along the Neches River, Brazos River, Caney Creek, Colorado River, and Arroyo Colorado to define the source of the nutrients and metals entering the waterway.

4. In land-cut reaches, the waterway has probably modified surface and subsurface hydrology.

When the waterway was cut through land areas, the groundwater table and generally the surface water level adjacent to the waterway were lowered to sea level. The waterway could act as a surface drain and alter runoff patterns during the wet season and carry salt water inland during the dry season. Satellite imagery and NASA high altitude color infrared aerial photography of the Galveston-Sabine reach of the waterway were studied. Variations in airphoto vegetation patterns about the waterway that could be attributed to land drainage or salt water intrusion were not readily apparent.

It is recommended that detailed hydrological and ecological studies be conducted at several locations in land-cut areas to evaluate the impact of the existing waterway on the groundwater and surface hydrology.

5. In shallow-open bay reaches of the waterway, the current patterns adjacent to the channel can have a significant affect on the shoaling rate.

Atturio, et al. (1976), in a study of the shoaling characteristics of the GIWW noted several reaches where shoaling rates were exceptionally high. A very high shoaling rate was noted in the Lower Laguna Madre between mile 657 and mile 660 and almost no shoaling was observed between mile 663 and mile 665. Circulation patterns in this part of the Laguna Madre were analyzed using satellite imagery. Between mile 657 and mile 660 the currents were generally always across the waterway while between mile 663 and mile 665 the currents were generally always parallel to the waterway. Similar current patterns and shoaling rates were observed in Matagorda Bay between mile 455 and mile 460.

In order to reduce dredging and the associated adverse environmental effects, it is recommended that current patterns in adjacent shallow bays be considered when planning modifications to the waterway.

Since satellite imagery of the Lower Laguna Madre indicated that bottom vegetation has a significant effect on turbidity and suspended sediment, it is further recommended that studies be conducted on promoting bottom vegetation in shallow bays.

6. The Intracoastal Waterway and associated dredged material islands have the potential of modifying the circulation patterns and salinity level in the bays and estuaries.

Texas bays are usually less than six feet deep while the channel is about 12 feet deep. The water movement is influenced by several factors including freshwater inflow, winds and tides. In general, circulation patterns in the shallow bays are strongly influenced by the wind while the currents in the waterway are strongly influenced by the tide.

The construction of the waterway through the land cut between the Upper and Lower Laguna Madre resulted in improved water circulation. Prior to construction of the Intracoastal Waterway and the Port Mansfield channel, the Lower Laguna Madre was an inaccessible, hypersaline, shallow bay with frequent fish kills. The improved circulation resulted in increased vegetative growth, increased fish landings and an increase in the range of juvenile brown shrimp.

It is recommended that model studies be conducted of proposed waterway modifications in shallow bays to optimize circulation patterns, control salinity levels and reduce maintenance dredging.

APPENDIX A

STRUCTURES ALONG THE WATERWAY

Table A-1. Bridges, Floodgates and Lakes

Table A-2. Pipelines and Cables

Table A-3. Barge Mooring and Turning Basins

TABLE A-1. Bridges, Floodgates and Locks

No.	Structure	Type	Location	Clearance Hor. (ft)	Clearance Vert. (ft)	GIWW Mileage
1	Bridge	Fixed	Hwy 73	400	136	286.4
2	Bridge	Fixed	Hwy 87	240	73	288.7
3	Bridge	Swing	RR & Hwy 124	100	10	319.2
4	Bridge	Bascule	RR	100	7	357.4
5	Bridge	Fixed	Hwy 75	105	75	357.5
6	Bridge	Fixed	Hwy 45	105	75	357.5
7	Bridge	Fixed	Hwy 332	201	73	393.7
8	Bridge	Pontoon	FM 1495	130	-	397.6
9	Floodgate	-	Brazos R.	75	-	400.7
10	Floodgate	-	Brazos R.	75	-	401.1
11	Bridge	Pontoon	FM 457	100	-	418.1
12	Bridge	Pontoon	FM 2031	141	-	440.8
13	Lock	-	Colorado R.	75X1200		441.3
14	Lock	-	Colorado R.	75X120		442.0
15	Bridge	Fixed	Hwy 361	125	48	533.2
16	Bridge	Fixed	Road 22	150	73	554.6
17	Bridge	Fixed	Hwy 100			
18	Bridge	Pontoon	Hwy 100	149	-	667.8

Table A-2. Pipelines and Cables

Structure	Type	Size in.	Clearance ft.	GIWW Mileage
Pipeline	gas	12 & 22	underground	266.7-268.4
Pipeline	oil	4,6,6,&36	underground	266.7-268.4
Cable	power	-	172	266.8
Pipeline	oil	8 & 22	underground	276.5
Pipeline	gas	12	underground	284.7-285.2
Cable	-	-	underground	284.7-285.2
Pipeline	gas	16	underground	286.3-286.5
Pipeline	gas	8	underground	288.6-288.8
Cable	power	-	125	288.7
Pipeline	gas	30	underground	293.6
Pipeline	gas	16	underground	306.7
Pipeline	gas	16	underground	316.0
Cable	-	-	83	319.2
Cable	power	-	110	319.2
Pipeline	gas	10	underground	322.0-322.7
Cable	power	-	93	322.5
Pipeline	gas	6	underground	333.2
Pipeline	gas	16	underground	345.5
Cable	-	-	underground	351.4-352.4
Pipeline	gas	12	underground	357.2-357.6
Cable	-	-	underground	357.2-357.6
Cable	power		99	357.45
Pipeline	oil	2.5,4.5,4.5	underground	383.2
Pipeline	gas	20	underground	392.9
Pipeline	gas	24	underground	393.7
Cable	power	-	97	393.72
Cable	-	-	74	394.83
Cable	power	-	108	395.7
Pipeline	gas	10	underground	397.4
Cable	telephone	-	underground	397.5
Cable	power	-	underground	397.6
Pipeline	gas	6"	underground	407.0

TABLE A-2. Pipelines and Cables (continued)

Structure	Type	Size in.	Clearance ft.	GIWW Mileage
Pipeline	gas	8	underground	417.5
Cable	telephone	-	73	418.0
Pipeline	-	8	underground	418.05
Cable	power	-	94	418.1
Pipeline	gas	20	underground	428.0
Cable	power	-	overhead	428.0
Pipeline	gas	8	underground	430.5
Pipeline	-	8	underground	431.3
Pipeline	gas	30	underground	434.0
Pipeline	gas	16	underground	434.9
Pipeline	gas	6	underground	434.9
Cable	power	-	71	440.8
Cable	power	-	underground	440.8
Pipeline	gas	30	underground	445.0
Cable	-	-	underground	470.3-470.5
Cable	-	-	underground	473.1-473.3
Cable	power	-	88	473.2
Pipeline	gas	-	underground	466.5
Pipeline	gas	4	underground	478.3
Pipeline	gas	8	underground	487.2
Pipeline	-	8	underground	491.5
Pipeline	gas	6,6	underground	501.6
Pipeline	gas	8	underground	521.8
Pipeline	gas	8	underground	522.2
Pipeline	gas	4	underground	526.8
Cable	power	-	61	533.2
Cable	telephone	-	79	533.2
Pipeline	oil	8", five 10", 12"		533.5-534.5
Pipeline	oil	2", 3", two 4", 6", two 16"		536.5
Pipeline	oil	2"	underground	539.1-539.5
Pipeline	water	8"	underground	539.1-539.5
Pipeline	gas	12	underground	539.1-539.5

TABLE A-2. Pipelines and Cables (continued)

Structure	Type	Size in.	Clearance ft.	GIWW Mileage
Cable	-	-	underground	551.3
Cable	power	-	93	553.0
Cable	power	-	91	554.6
Cable	-	-	underground	554.6-554.9
Pipeline	gas	6	underground	554.6-554.9
Pipeline	-	6	underground	554.6-554.9
Pipeline	gas	12	underground	563.2
Pipeline	gas	10	underground	569.7
Pipeline	gas	12	underground	574.0
Pipeline	gas	10	underground	575.5
Pipeline	gas	10	underground	586.0
Pipeline	gas	6	underground	602.5
Pipeline	gas	6	underground	625.0
Pipeline	gas	4"	underground	636.8

Table A-3. Barge Moorings and Turning Basins

STRUCTURE	DIMENSION ft x ft	GIWW MILEAGE
Barge Mooring Basin	75 x 2300	288.5
Barge Mooring Basin	300 x 5500	346.5
Barge Mooring Basin	75 x 3000	351.8
Barge Mooring Basin	110 x 2300	374.2
Barge Mooring Basin	65 x 5000	455.0
Barge Mooring Basin	50 x 5000	475.8
Barge Mooring Basin	110 x 2150	491.5
Barge Mooring Basin	100 x 2500	540.2
Port Isabel Turning Basin		669.1
Brownsville Turning Basin		683.8

APPENDIX B

COMMERCIAL TRAFFIC ON THE WATERWAY

TABLE B-1. Vessel Trips on the Gulf Intracoastal Waterway, East Bound, REACH I, 1973

Draft ft.	Self-Propelled Passenger & Dry Cargo	Self-Propelled Tanker	Tow-Boat or Tug-Boat	Barges Towed Dry	Barges Towed Tanker	Total East-Bound
14			10		11	21
13			189		7	196
12			682	5	180	867
11			1,608	35	435	2,078
10	5		222	92	1,432	1,751
9	3		1,885	9,110	5,685	8,483
8	10		1,961	308	1,327	3,606
7	24		1,341	121	221	1,707
6 and less	29		2,131	2,746	5,235	10,141
TOTAL	71		10,029	4,217	19,533	28,856

TABLE B-2. Vessel Trips on the Gulf Intracoastal Waterway West Bound, REACH I, 1973

Draft ft.	Self-Propelled Passenger & Dry Cargo	Self-Propelled Tanker	Tow-Boat or Tug-Boat	Barges Towed Dry	Barges Towed Tanker	Total West-Bound
14		7	7		6	14
13			208		13	221
12	1		688	5	391	1,085
11	1		1,401	135	626	2,163
10	4		227	228	1,839	2,298
9	4		1,931	1,154	2,985	6,074
8	4		1,938	1,218	1,319	4,479
7	25		1,303	310	272	1,910
6 and less	42	1	2,447	1,275	7,177	10,942
TOTAL	81	2	10,150	4,325	14,628	29,186

TABLE B-3. Vessel Trips on the Gulf Intracoastal Waterway East Bound, REACH II, 1973

Draft ft.	Self-Propelled Passenger & Dry Cargo	Self-Propelled Tanker	Tow-Boat or Tug-Boat	Barges Towed Dry	Barges Towed Tanker	Total East-Bound
12	3		6	3	101	113
11	5			65	214	284
10	76		523	368	359	1,326
9	29		479	531	1,599	2,638
8	291		1,341	222	1,130	2,984
7	123		3,201	727	100	4,151
6 and less	1,748	3	1,969	5,808	3,021	12,549
TOTAL	2,275	3	7,519	7,724	6,524	24,045

TABLE B-4. Vessel Trips on the Gulf Intracoastal Waterway West Bound, REACH II, 1973

Draft ft.	Self-Propelled Passenger & Dry Cargo	Self-Propelled Tanker	Tow-Boat or Tug-Boat	Barges Towed Dry	Barges Towed Tanker	Total West-Bound
12	3		6	3	113	125
11	19			202	185	406
10	77		491	2,896	651	4,115
9	42		450	1,679	1,753	3,924
8	321		1,365	1,060	521	3,267
7	88		3,316	261	116	3,781
6 and less	1,608	2	1,859	1,687	3,114	8,270
TOTAL	2,158	2	7,487	7,788	6,453	23,888

TABLE B-5. Vessel Trips on the Gulf Intracoastal Waterway, East Bound, REACH III, 1973

Draft ft.	Self-Propelled		Tow-Boat or Tug-Boat	Barges Towed		Total East-Bound
	Passenger & Dry Cargo	Tanker		Dry	Tanker	
12			1		23	24
11					43	43
10	1		7	16	89	113
9	730		147	169	182	1,228
8	1,180		213	26	62	1,481
7			158	18	21	197
6 and less	12,279	1	371	387	506	13,544
TOTAL	14,190	1	897	616	926	16,630

TABLE B-6. Vessel Trips on the Gulf Intracoastal Waterway, West Bound, REACH III, 1973

Draft ft.	Self-Propelled: Passenger & Dry Cargo	Self-Propelled: Tanker	Tow-Boat or Tug-Boat	Barges Towed: Dry	Barges Towed: Tanker	Total West-Bound
12					5	5
11				7	12	19
10	1		8	22	38	69
9	288		140	228	143	799
8	1,178		231	24	177	1,592
7	3		160	82	3	248
6 and less	12,714	1	358	282	546	13,901
TOTAL	14,184	1	879	645	924	16,633

Note: Some duplication of trips may exist as a result of vessels engaged in combined foreign and domestic movements. Excluded from data are military vessels.

Source: Waterborn Commerce of the United States, Part 2, 1973, Dept. of the Army, U.S. Corps of Engineers.

APPENDIX C

WATER AND SEDIMENT QUALITY

Table C-1. Physical Water Quality, January 1975

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
265.4	28	<1	<1	8.9	8.6	81.1	78.4	11	11	26	27	7.3	7.3	437	445
265.6	26	<1	<1	9.0	9.2	81.6	83.4	11	11	26	28	7.4	7.3	430	448
265.8	24	<1	<1	8.4	8.8	76.2	79.8	11	11	57	52	7.5	7.4	434	421
274.2	10	<1	<1	8.4	8.6	76.2	78.0	11	11	55	52	7.4	7.3	419	416
274.4	20	<1	<1	8.4	8.4	76.2	76.2	11	11	58	60	7.5	7.4	405	414
274.8	32	<1	<1	8.4	8.4	76.2	76.2	11	11	54	50	7.7	7.5	419	419
275.9	28	<1	<1	8.3	8.2	75.2	74.3	11	11	48	52	7.6	7.5	415	425
278.0	20	<1	<1	9.0	9.0	84.0	87.7	12	14	74	90	7.4	7.3	414	416
280.1	30	<1	<1	9.1	8.0	84.9	76.3	12	13	52	55	7.4	7.3	415	416
281.2	35	<1	<1	8.4	8.2	78.4	78.2	12	13	50	52	7.2	7.2	420	420
282.4	40	<1	<1	8.4	8.8	78.4	82.1	12	12	56	57	7.4	7.2	419	419
285.0	35	<1	<1	8.4	8.4	78.4	80.1	12	13	63	65	7.3	7.3	416	421
285.5	30	<1	<1	8.4	8.6	80.1	82.0	13	13	67	71	7.5	7.4	416	421
288.1	25	<1	<1	8.2	8.2	78.2	78.2	13	13	75	77	7.2	7.2	424	425
289.5	13	<1	<1	8.8	8.4	78.2	74.7	10	10	100	105	7.5	7.4	425	426
290.0	14	<1	<1	8.2	8.6	72.9	76.5	10	10	105	105	7.4	7.5	418	423
291.6	10	1	2	9.8	9.6	85.1	83.8	9	9	95	97	7.6	7.6	432	432

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
294.6	13	1	2	9.6	9.8	85.4	89.2	10	11	94	96	7.2	7.3	427	427
296.6	13	1	1	8.6	8.8	76.5	78.2	10	10	72	77	7.3	7.4	432	430
298.6	15	1	1	9.2	8.8	77.9	74.5	8	8	71	71	7.5	7.5	424	425
301.2	15	1	1	8.0	8.0	74.7	74.7	12	12	87	89	7.5	7.4	417	420
303.0	10	1	1	7.2	7.0	68.7	66.7	13	13	105	105	7.3	7.3	424	419
305.0	12	1	1	6.8	6.6	64.8	62.9	13	13	106	110	7.3	7.3	429	429
305.4	15	<1	<1	6.6	5.6	62.9	53.4	13	13	110	110	7.4	7.4	420	425
307.2	14	<1	<1	6.8	7.0	64.8	66.7	13	13	105	110	7.3	7.2	423	424
309.4	15	<1	<1	7.8	7.6	69.4	68.9	10	11	100	100	7.4	7.3	429	429
310.9	15	<1	<1	8.0	7.6	71.1	68.9	10	11	94	98	7.4	7.4	429	427
312.9	11	<1	<1	8.2	7.8	72.9	70.7	10	11	98	102	7.4	7.4	436	428
315.0	12	<1	<1	8.2	7.8	74.3	72.8	11	12	100	94	7.4	7.4	429	429
316.4	13	<1	<1	8.2	7.8	74.3	72.8	11	12	95	76	7.3	7.3	427	421
319.0	10	1	1	8.0	7.9	74.7	73.7	12	12	83	66	7.3	7.4	428	423
320.5	15	<1	<1	7.8	8.0	69.4	72.5	10	11	108	105	7.2	7.2	440	437
321.2	15	<1	<1	7.8	8.0	69.4	71.1	10	10	102	102	7.2	7.2	440	441
323.0	9	<1	<1	8.0	8.2	72.5	74.3	11	11	105	105	7.3	7.3	443	439

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
325.0	8	<1	<1	8.0	8.0	72.5	72.5	11	11	110	108	7.2	7.1	444	443
326.5	8	<1	<1	8.0	8.0	72.5	72.5	11	11	105	108	7.3	7.2	444	442
327.6	10	1	2	8.0	8.0	71.1	72.8	10	11	110	108	7.3	7.3	439	438
329.8	11	1	3	8.2	8.2	72.9	75.8	10	11	102	102	7.3	7.4	441	437
331.4	12	3	4	8.2	8.4	73.9	78.1	10	11	94	86	7.4	7.5	436	437
332.3	12	4	5	8.8	8.4	79.6	78.5	10	11	82	84	7.6	7.5	437	437
333.6	12	4	5	8.8	8.4	79.6	78.5	10	11	58	67	7.6	7.5	435	434
337.7	11	6	7	9.0	9.2	82.4	86.9	10	11	42	38	7.8	7.8	442	434
339.2	12	8	8	9.2	9.4	85.5	90.5	10	11	31	36	7.8	7.7	439	438
342.5	12	6	8	11.1	9.8	101.7	91.1	10	10	29	29	3.3	8.1	442	441
346.2	12	7	9	10.0	10.2	92.5	95.4	10	10	39	38	8.2	8.1	440	439
347.0	11	9	10	10.0	9.9	91.3	93.0	9	10	32	28	8.0	8.0	454	451
350.2	15	10	13	10.4	10.4	97.7	102.1	10	11	16	18	8.3	8.3	450	447
351.2	12	12	18	9.0	10.0	85.6	101.3	11	11	15	15	8.5	8.4	451	445
353.4	12	20	11	11.1	9.0	113.9	87.2	11	11	8	16	8.4	8.6	449	441
355.1	12	20	14	10.8	8.8	108.0	88.9	10	12	13	26	8.5	8.4	455	449
358.2	12	12	13	10.8	10.4	100.5	99.6	9	10	12	13	8.6	8.5	455	452

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
359.7	12	12	13	10.6	10.2	98.7	97.7	9	10	12	14	8.5	8.5	453	452
361.4	14	12	12	10.8	10.2	100.5	97.0	9	10	18	12	8.6	8.5	447	447
362.4	14	12	12	10.6	10.2	98.7	97.0	9	10	22	20	8.5	8.5	455	452
364.0	13	12	12	10.4	10.0	96.8	95.1	9	10	18	14	8.4	8.4	453	448
366.4	14	10	12	10.6	10.0	99.6	95.1	10	10	20	18	8.3	8.3	449	442
368.0	13	12	12	10.6	9.4	100.8	91.6	10	11	13	16	8.2	8.2	451	446
370.0	10	12	12	10.2	10.0	97.0	97.5	10	11	14	21	8.2	8.2	442	436
372.0	12	13	13	9.8	9.8	93.8	96.2	10	11	34	41	8.4	8.5	435	435
374.0	13	12	13	10.0	9.8	95.1	93.8	10	10	15	17	8.4	8.5	444	439
376.8	8	11	14	9.2	10.2	87.0	100.7	10	11	10	14	8.5	8.4	444	439
379.9	9	11	8	9.3	9.6	90.2	91.3	11	11	25	31	8.4	8.4	447	444
381.3	12	6	7	9.8	9.8	89.8	90.6	10	10	46	51	8.2	8.2	457	453
384.5	11	10	11	9.4	9.6	88.3	90.8	10	10	29	34	8.2	8.2	451	442
388.0	11	14	15	9.8	9.8	96.8	99.7	11	12	28	38	8.4	8.3	451	448
389.9	10	19	19	8.6	8.8	89.7	91.8	13	13	37	38	8.4	8.4	440	442
391.6	10	18	19	8.9	9.0	92.3	93.9	12	13	40	38	8.4	8.4	441	439
392.4	10	18	18	8.8	8.8	91.3	93.2	12	13	28	44	8.4	8.4	439	436
393.0	13	13	21	7.8	7.4	79.4	80.0	12	13	60	40	8.5	8.5	448	442

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
398.4	13	5	8	9.0	8.6	85.8	85.4	12	13	52	115	8.6	8.5	447	443
399.9	14	5	7	9.5	9.4	90.6	94.0	12	13	52	115	8.6	8.5	443	435
400.8	14	6	6	9.8	9.0	96.5	90.4	13	14	75	120	8.8	8.7	450	445
402.0	14	6	8	8.8	8.6	84.5	83.8	12	12	82	74	8.5	8.3	451	449
402.9	13	6	8	9.0	8.8	86.4	85.8	12	12	42	75	8.2	8.2	453	450
404.4	12	7	9	9.0	9.0	85.0	86.1	11	11	60	67	8.3	8.3	453	443
405.0	12	7	12	8.6	9.0	81.2	89.6	11	12	27	31	8.1	8.2	451	451
406.0	11	13	14	8.8	9.0	81.4	93.1	11	13	22	28	8.2	8.2	450	441
408.8	9	12	13	9.8	9.6	91.2	88.8	9	11	14	22	8.2	8.2	455	450
411.5	10	8	12	10.2	10.0	92.5	95.1	9	10	18	20	8.1	8.1	451	448
412.8	12	11	12	9.4	9.6	86.9	91.3	9	10	22	24	8.3	8.2	458	455
415.1	12	11	12	9.4	9.8	86.9	93.2	9	10	21	24	8.4	8.3	454	451
417.8	12	11	12	9.8	9.2	90.6	87.5	9	10	29	28	8.3	8.4	457	456
419.7	10	7	11	10.0	9.6	94.5	93.1	11	11	25	27	8.3	8.4	456	452
421.5	11	11	12	10.0	10.2	94.6	97.0	10	10	27	42	8.3	8.2	456	453
423.4	12	10	11	9.6	9.6	88.2	90.8	9	10	23	20	8.3	8.8	457	455
428.4	11	10	13	10.2	10.2	98.2	100.1	11	11	20	32	8.4	8.3	445	443
430.1	12	12	13	10.0	10.4	95.1	99.6	10	10	20	23	8.3	8.4	457	455

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
431.8	11	13	13	9.8	9.6	93.8	91.9	10	10	20	38	8.3	8.2	458	454
434.8	10	11	12	9.8	9.8	92.7	93.2	10	10	22	22	8.3	8.3	458	457
437.3	9	10	11	10.2	10.2	98.2	98.9	11	11	21	24	8.4	8.5	456	454
438.4	10	7	8	9.2	9.2	89.1	108.6	12	11	25	25	8.2	8.2	458	458
440.7	11	6	7	9.4	9.2	90.3	89.1	12	12	30	30	8.2	8.2	456	456
441.5	11	2	4	9.0	9.4	82.4	89.3	11	12	30	32	8.1	8.1	463	460
442.5	12	3	3	10.0	10.0	94.3	96.5	12	13	25	32	8.2	8.2	464	461
444.2	12	2	2	9.6	9.8	90.1	94.2	12	13	28	30	8.2	8.2	461	466
447.0	12	3	3	9.4	9.4	88.7	88.7	12	12	32	28	8.3	8.2	463	462
449.8	12	4	4	8.8	8.7	85.7	84.7	13	13	22	30	8.3	8.3	458	457
452.7	11	8	10	9.5	9.8	96.8	100.9	14	13	23	27	8.4	8.5	456	451
453.5	12	11	11	9.8	9.6	101.6	98.3	14	13	27	22	8.3	8.4	451	450
456.1	12	16	15	10.0	9.8	104.8	99.7	13	12	50	29	8.5	8.5	455	453
460.4	12	23	19	9.3	9.3	103.7	97.0	14	12	10	17	8.4	8.4	450	453
462.2	10	28	20	9.3	9.5	104.7	99.7	13	12	10	10	8.3	8.3	456	453
464.5	12	30	21	9.3	9.2	105.9	99.4	13	13	9	10	8.4	8.4	454	454
466.2	13	29	25	9.5	9.3	107.6	105.0	13	14	8	36	8.4	8.4	456	449
469.5	11	27	25	9.3	9.2	106.1	103.9	14	14	14	15	8.4	8.4	455	455

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T		T	B	T	B	T	B	T	B	T	B
471.2	12	24	24	9.4	9.3	103.3	102.2	14	13	12	13	8.4	8.3	456	458
471.9	10	22	23	9.6	9.4	104.2	104.1	13	13	9	9	8.3	8.3	445	440
476.5	11	23	23	10.0	10.4	110.8	116.0	13	14	7	7	8.4	8.4	446	441
479.0	13	23	22	10.4	9.0	115.2	99.7	13	14	7	8	8.4	8.4	455	451
481.2	12	23	21	9.6	9.4	107.0	101.6	13	13	7	7	8.3	8.3	457	455
485.2	12	16	16	10.0	9.0	99.7	92.0	11	12	7	10	8.5	8.4	454	454
488.7	12	12	12	9.8	9.6	93.2	93.6	10	11	12	12	8.4	8.4	459	454
492.0	13	9	9	11.2	9.6	104.8	91.8	10	11	10	11	8.5	8.4	459	458
495.4	12	5	6	13.0	13.2	121.5	126.7	11	12	9	10	8.9	9.0	457	447
496.6	12	6	6	12.8	12.8	120.1	122.9	11	12	11	13	8.9	9.0	455	445
498.4	12	7	7	11.2	11.6	105.8	112.3	11	12	10	15	8.8	8.9	452	447
500.4	10	7	7	10.4	10.4	100.7	100.7	12	12	11	13	8.8	8.8	458	459
503.1	11	8	8	10.0	10.2	97.5	101.3	12	13	12	12	8.7	8.6	458	459
505.2	12	8	8	10.4	10.4	103.3	103.3	13	13	13	13	8.4	8.5	456	458
507.1	13	8	8	10.2	11.0	101.3	107.2	13	12	15	12	8.4	8.5	448	448
510.0	12	9	9	9.6	9.6	94.0	94.0	12	12	12	16	8.4	8.5	452	454
511.5	11	9	9	10.2	10.4	99.9	101.8	12	12	13	14	8.4	8.4	452	451
515.4	12	11	13	9.6	9.3	95.9	95.5	12	13	12	15	8.4	8.4	454	449

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
517.5	11	11	14	9.8	9.4	97.9	97.2	12	13	9	6	8.4	8.5	456	449
524.2	6	15	15	10.8	9.6	112.5	100.0	13	13	6	6	8.4	8.4	458	455
526.0	12	17	17	9.8	9.0	105.4	96.8	14	14	6	7	8.2	8.2	455	449
530.1	11	19	19	8.6	8.6	96.4	96.4	15	15	6	7	8.4	8.5	453	452
531.6	11	20	21	8.4	8.5	92.0	93.7	14	14	6	6	8.4	8.3	456	446
536.3	12	26	26	9.2	8.8	108.8	104.1	16	16	12	10	8.4	8.4	453	454
538.5	11	26	24	8.6	8.4	99.5	96.1	15	15	8	10	8.3	8.3	455	455
542.0	11	23	24	8.6	8.2	96.4	91.9	14	14	6	13	8.2	8.2	452	452
543.6	12	23	23	8.4	8.4	93.7	93.7	14	14	7	10	8.3	8.4	439	441
545.8	12	24	24	8.6	8.4	96.4	94.1	14	14	5	5	8.3	8.3	441	441
548.8	12	23	24	9.6	9.0	107.0	98.9	14	13	8	6	8.3	8.3	442	445
551.8	11	24	25	9.4	9.0	107.6	103.7	15	15	6	8	8.2	8.3	448	448
552.2	11	24	25	9.4	9.2	107.6	106.0	15	15	6	9	8.2	8.2	442	441
553.7	12	25	26	9.4	9.4	110.6	111.2	16	16	6	11	8.3	8.3	448	442
555.6	11	25	25	9.2	9.6	106.0	110.6	15	15	6	10	8.1	8.2	451	449
557.4	12	25	24	8.8	9.4	100.7	105.3	14	14	5	9	8.1	8.0	444	431
558.5	12	26	25	8.5	9.4	99.9	107.6	14	14	5	8	8.1	8.1	451	446

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
559.8	12	26	26	9.4	9.4	108.8	108.8	15	15	5	10	8.1	8.1	440	440
561.8	13	23	24	9.8	9.6	109.3	107.6	14	14	6	6	8.0	8.0	454	449
565.3	10	23	25	8.8	8.8	99.9	101.4	15	15	5	7	8.1	8.0	453	452
568.2	11	23	24	8.4	8.4	93.1	94.1	13	14	5	6	8.2	8.2	455	453
571.6	12	26	26	8.4	8.4	97.2	95.3	15	14	5	8	8.1	8.1	451	451
574.6	10	26	26	8.4	8.4	97.2	95.3	15	14	6	7	8.2	8.1	451	449
577.7	11	27	27	8.5	8.6	98.9	100.0	15	15	6	7	8.1	8.2	461	451
580.8	11	30	30	8.8	8.9	102.0	103.2	14	14	10	10	8.2	8.1	453	453
583.9	10	30	30	8.6	8.8	99.7	100.2	14	13	9	32	8.3	8.4	449	439
587.0	17	29	30	9.2	8.8	106.3	102.0	14	14	5	8	8.0	8.2	450	444
589.8	10	29	30	8.8	8.6	103.8	99.7	15	14	6	12	8.2	8.2	453	448
593.0	11	30	30	8.4	8.2	97.4	95.1	14	14	10	25	8.2	8.2	452	447
595.8	11	31	31	8.5	8.4	103.5	100.2	16	15	7	12	8.3	8.3	451	446
599.9	12	31	31	8.6	8.4	102.6	98.2	15	14	6	7	8.3	8.3	449	448
602.0	11	31	31	8.2	8.2	95.9	95.9	14	14	7	7	8.2	8.1	451	445
605.0	9	31	31	8.4	8.4	98.2	98.2	14	14	19	14	8.2	8.2	463	464

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
609.0	10	31	31	8.4	8.2	98.2	97.8	14	15	8	8	8.1	8.2	452	451
612.9	11	31	31	8.8	8.4	102.9	98.2	14	14	8	10	8.3	8.2	450	450
615.7	11	33	33	8.4	8.2	103.6	101.1	15	15	12	20	8.1	8.1	457	451
619.1	12	31	31	8.4	8.1	98.2	93.1	14	13	7	23	8.2	8.1	437	438
622.0	11	33	32	8.5	8.4	104.8	98.9	16	14	8	24	8.3	8.2	452	450
625.0	12	32	30	8.5	8.3	104.1	98.7	16	15	8	31	8.1	8.0	454	443
628.0	11	31	31	8.6	8.1	104.8	94.7	16	14	8	20	8.1	8.0	454	450
631.4	12	28	30	8.8	8.2	103.2	97.5	15	15	8	13	8.2	8.1	444	445
635.1	13	29	29	8.6	8.0	99.4	92.5	14	14	8	28	8.0	7.9	455	453
638.3	11	30	28	8.2	7.6	101.3	89.2	17	15	13	13	8.1	8.0	450	450
640.7	12	30	29	8.8	7.2	114.8	86.6	20	16	12	13	8.2	8.8	444	442
644.1	12	20	30	11.6	8.6	138.2	106.2	18	17	10	10	8.2	8.0	454	444
647.7	11	23	25	9.6	8.8	114.0	105.2	17	16	22	22	8.4	8.1	448	448
650.8	12	25	24	10.4	8.8	124.7	102.9	17	16	15	29	8.2	8.0	453	453
653.8	12	27	26	10.2	8.5	126.2	102.6	18	17	21	47	8.1	8.0	453	453
656.9	11	28	26	8.4	7.8	104.5	94.2	18	17	18	18	8.3	8.3	454	452
659.9	11	24	24	9.0	8.4	107.6	100.3	17	17	12	53	8.9	8.1	451	446

Table C-1. (continued)

GIWW Mileage Statute Miles	Depth (ft)	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp (°C)		Turbidity (FTU)		pH		Eh (mv)	
		T	B	T	B	T	B	T	B	T	B	T	B	T	B
663.1	10	24	25	9.2	8.0	110.0	95.9	17	17	13	28	8.2	8.1	452	452
666.5	11	26	25	8.0	7.6	94.6	89.5	16	16	18	12	8.2	8.0	451	441
668.9	15	24	26	8.2	7.8	95.9	92.3	16	16	7	9	7.8	8.1	447	441
671.7	35	26	26	8.2	7.8	99.0	92.3	17	16	8	8	8.2	8.1	448	444
675.2	32	26	26	8.4	8.6	101.4	101.7	17	16	6	12	8.0	8.1	457	458
678.3	33	28	27	8.0	7.6	97.6	92.3	17	17	7	14	8.2	8.1	457	456
682.1	32	27	27	9.8	8.4	121.3	104.0	18	18	8	12	8.3	8.1	456	451

Table C-2. Chemical Water Quality, January 1975

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l) T	TOC (mg/l) B
265.4	0.042	<0.02	0.10	<0.05	34	4	6	7
274.2	0.010	0.05	0.12	<0.05	289	44	7	8
278.0	0.066	0.09	0.07	<0.05	96	18	8	8
285.0	0.057	0.08	0.07	<0.05	181	18	8	8
290.0	0.160	0.10	0.18	<0.05	64	7	9	9
296.6	0.062	0.06	0.17	<0.05	198	34	8	8
301.2	0.095	0.10	0.10	<0.05	285	29	8	7
305.4	0.131	0.12	0.09	<0.05	461	41	7	-
309.4	0.115	0.29	0.12	<0.05	574	52	-	-
315.0	0.069	0.10	0.14	<0.05	296	32	7	-
319.0	0.065	0.10	0.10	<0.05	526	45	8	8
320.5	0.150	0.02	0.20	<0.05	230	26	8	8
326.5	0.067	0.09	0.15	<0.05	438	52	7	6
329.8	0.120	0.12	0.12	<0.05	200	28	7	6
332.3	0.089	<0.02	0.08	<0.05	715	76	6	7

Table C-2. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l) T	TOC (mg/l) B
337.7	0.100	<0.02	<0.05	<0.05	133	22	6	6
342.5	0.263	0.26	0.06	<0.05	82	16	5	5
346.2	0.234	<0.02	<0.05	<0.05	228	38	5	5
350.2	0.530	<0.02	<0.05	<0.05	70	15	5	4
358.2	0.278	0.05	<0.05	<0.05	162	44	4	4
362.4	<0.010	0.08	<0.05	<0.05	116	34	4	5
368.0	0.225	<0.02	<0.05	<0.05	490	14	4	4
374.0	0.255	0.05	<0.05	<0.05	123	34	4	4
379.9	0.234	0.04	0.09	<0.05	109	32	4	4
388.0	0.118	0.05	<0.05	<0.05	98	24	3	4
392.4	0.147	0.12	0.05	<0.05	101	26	2	3
399.9	0.089	0.33	0.37	<0.05	547	47	3	4
400.8	0.168	0.22	0.48	<0.05	182	30	3	4
402.0	0.258	0.20	0.24	<0.05	272	36	3	3
404.4	0.240	0.05	0.13	<0.05	320	39	4	3

Table C-2. (continued)

GIWW Mileage Statute Miles	PO_4 -P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)	
							T	R
405.0	0.140	<0.02	0.09	<0.05	130	30	4	5
406.0	0.128	<0.02	<0.05	<0.05	86	16	4	3
411.5	0.090	0.04	<0.05	<0.05	82	16	4	4
417.8	0.131	0.15	<0.05	<0.05	88	22	3	3
421.5	0.103	0.06	<0.05	<0.05	555	17	3	3
428.4	0.120	0.12	<0.05	<0.05	135	36	3	3
434.8	0.070	<0.02	<0.05	<0.05	84	19	3	4
437.3	0.092	<0.02	<0.05	<0.05	77	16	3	4
440.7	0.110	<0.02	0.28	<0.05	243	40	2	3
441.5	0.135	<0.02	0.58	<0.05	92	10	<2	<2
442.5	0.067	<0.02	0.54	<0.05	101	16	<2	2
447.0	0.064	<0.02	0.47	<0.05	107	11	<2	3
453.5	0.129	<0.02	0.18	<0.05	86	17	2	2
460.4	0.066	<0.02	<0.05	<0.05	144	38	2	5
465.2	0.049	<0.02	<0.05	<0.05	61	16	4	4
471.2	0.131	<0.02	<0.05	<0.05	170	48	4	<2

Table C-2. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l) 1	TOC (mg/l) 3
479.0	0.035	<0.02	<0.05	<0.05	64	16	4	4
485.2	0.057	0.03	<0.05	<0.05	34	20	4	4
492.0	0.171	<0.02	0.09	<0.05	102	27	5	5
498.4	0.175	<0.02	<0.05	<0.05	198	18	5	6
505.2	0.132	<0.02	<0.05	<0.05	66	26	5	5
510.0	0.141	0.06	<0.05	<0.05	952	22	5	5
517.5	0.085	<0.02	<0.05	<0.05	106	34	5	5
524.2	0.084	0.03	<0.05	<0.05	98	24	5	5
530.1	0.078	<0.02	<0.05	<0.05	124	25	5	5
536.3	0.038	<0.02	<0.05	<0.05	180	55	5	4
542.0	0.057	<0.02	<0.05	<0.05	158	44	4	4
548.8	0.034	<0.02	<0.05	<0.05	178	40	4	4
555.6	0.035	<0.02	<0.05	<0.05	76	17	5	4
561.8	0.015	<0.02	<0.05	<0.05	116	26	5	5
568.2	0.015	<0.02	<0.05	<0.05	120	30	4	5

Table C-2. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l) T	TOC (mg/l) S
574.6	0.029	<0.02	<0.05	<0.05	85	18	5	5
580.8	0.032	<0.02	<0.05	<0.05	256	54	5	5
587.0	0.034	<0.02	<0.05	<0.05	59	13	5	5
593.0	0.023	0.10	<0.05	<0.05	119	22	5	5
599.9	0.032	<0.02	0.05	<0.05	82	16	6	5
605.0	0.035	0.12	<0.05	<0.05	156	69	6	5
612.9	0.048	0.05	0.19	<0.05	142	33	6	7
619.1	0.035	<0.02	<0.05	<0.05	100	20	6	6
625.0	0.048	0.10	<0.05	<0.05	77	17	6	6
631.4	0.038	<0.02	<0.05	<0.05	120	73	5	6
638.3	0.057	<0.02	<0.05	<0.05	138	24	6	5
644.1	0.096	0.05	<0.05	<0.05	83	18	6	5
650.8	0.060	0.26	0.13	<0.05	92	18	5	5
656.9	0.014	0.02	<0.05	<0.05	143	30	5	5
663.1	<0.010	<0.02	<0.05	<0.05	246	66	4	4

Table C-2. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)	
							T	B
668.9	0.052	<0.02	<0.05	<0.05	314	53	4	4
675.2	0.028	<0.02	<0.05	<0.05	123	35	4	3
682.1	0.065	<0.02	<0.05	<0.05	130	32	4	4

Table C-3. Metals in Water, January 1975

GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)	Zn (ppb)	GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)	Zn (ppb)
265.4	<1.5	5	5	70	342.5	<1.5	4	3	2
274.2	<1.5	2	5	26	346.2	<1.5	<1.5	3	5
278.0	<1.5	13	8	24	350.2	<1.5	2	2	4
285.0	<1.5	13	<1.5	25	353.4	<1.5	<1.5	3	5
290.0	<1.5	9	3	39	358.2	<1.5	20	6	16
296.6	<1.5	3	5	12	362.4	<1.5	3	<1.5	7
301.2	<1.5	<1.5	<1.5	9	368.0	<1.5	4	4	<1
305.4	<1.5	4	<1.5	4	374.0	<1.5	3	2	4
309.4	<1.5	12	6	24	379.9	<1.5	4	<1.5	<1
315.0	<1.5	6	<1.5	8	388.0	<1.5	7	<1.5	10
319.0	<1.5	<1.5	2	12	392.4	<1.5	6	5	<1
320.5	<1.5	4	<1.5	10	399.9	<1.5	5	<1.5	<1
326.5	<1.5	3	3	11	400.8	<1.5	4	<1.5	7
329.8	<1.5	<1.5	9	4	402.0	<1.5	6	<1.5	2
332.3	<1.5	<1.5	<1.5	10	404.4	<1.5	2	<1.5	4
337.7	<1.5	<1.5	2	5	405.0	<1.5	3	<1.5	2

Table C-3. (continued)

GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)	Zn (ppb)	GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)	Zn (ppb)
406.0	<1.5	5	<1.5	3	485.2	<1.5	<1.5	<1.5	<1
411.5	<1.5	5	6	2	492.0	<1.5	<1.5	<1.5	<1
417.8	<1.5	5	<1.5	3	498.4	<1.5	<1.5	<1.5	<1
421.5	<1.5	2	<1.5	<1	505.2	<1.5	<1.5	<1.5	<1
428.4	<1.5	4	<1.5	<1	510.0	<1.5	<1.5	<1.5	<1
434.8	<1.5	4	<1.5	<1	517.5	<1.5	<1.5	<1.5	<1
437.3	<1.5	6	<1.5	<1	524.2	<1.5	2	<1.5	<1
440.7	<1.5	4	<1.5	5	530.1	<1.5	<1.5	<1.5	<1
441.5	<1.5	7	<1.5	<1	536.3	<1.5	<1.5	<1.5	<1
442.5	<1.5	<1.5	<1.5	<1	542.0	<1.5	<1.5	<1.5	<1
447.0	<1.5	<1.5	<1.5	<1	548.8	<1.5	<1.5	<1.5	9
453.5	<1.5	<1.5	<1.5	<1	555.6	<1.5	<1.5	<1.5	<1
460.4	<1.5	<1.5	<1.5	<1	561.8	<1.5	4	<1.5	42
466.2	<1.5	<1.5	<1.5	<1	568.2	<1.5	11	<1.5	21
471.2	<1.5	<1.5	<1.5	<1	574.6	<1.5	5	<1.5	11
479.0	<1.5	<1.5	<1.5	<1	580.8	<1.5	10	<1.5	18

Table C-3. (continued)

GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)	Zn (ppb)	GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)	Zn (ppb)
587.0	<1.5	4	<1.5	6	638.3	<1.5	5	<1.5	400
593.0	<1.5	2	<1.5	4	644.1	<1.5	2	<1.5	5
599.9	<1.5	4	<1.5	9	650.8	<1.5	4	<1.5	12
605.0	<1.5	2	<1.5	10	656.9	<1.5	3	<1.5	15
612.9	<1.5	3	<1.5	2	663.1	<1.5	5	<1.5	6
619.1	<1.5	6	<1.5	70	668.9	<1.5	4	<1.5	12
625.0	<1.5	4	<1.5	12	675.2	<1.5	3	<1.5	7
631.4	<1.5	4	<1.5	7	682.1	<1.5	3	<1.5	12

Table C-4. Sediment Analysis, January 1975

GIWW Mileage Statute Miles	Sediment Classification	pH	Eh	BOD_5 (ppm)	% Vol. Solids	Cd (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
265.4	sandy	7.6	72	394	4.16	<0.18	4.6	7.1	13
274.2	silty	8.4	33	1062	5.86	2.7	18.0	37.0	57
278.0	clayey	---	---	310	2.48	<0.20	8.5	18.0	30
285.0	silty	7.2	56	917	5.69	<0.34	12.0	23.0	44
290.0	sandy	---	129	1126	4.19	<0.17	22.0	87.0	44
296.6	clayey	---	-22	319	1.49	<0.23	4.4	14.0	12
301.2	sandy	---	124	506	2.05	<0.24	9.6	50.0	24
305.4	silty	7.8	35	509	2.34	<0.25	6.4	12.0	21
309.4	sandy	7.2	281	----	----	---	---	---	---
315.4	sandy	7.0	285	1047	2.63	<0.24	6.9	14.0	24
319.0	sandy	7.1	23	485	2.26	<0.21	7.4	17.0	20
320.5	silty	7.2	73	1934	3.88	<0.31	12.0	22.0	44
326.5	silty	7.3	28	1533	4.25	<0.29	9.6	25.0	53
329.8	sandy	7.8	203	349	1.73	<0.23	3.8	6.8	19
332.3	sandy	7.2	50	1130	2.46	<0.19	4.5	8.2	29
337.7	sandy	7.3	45	393	2.21	<0.25	7.7	9.2	30

Table C-4. (continued)

GIWW Mileage Statute Miles	Sediment Classification	pH	Eh	BOD_5 (ppm)	% Vol. Solids	Cd (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
342.5	sandy	7.6	56	310	0.35	0.54	3.8	4.8	8
346.2	sandy	7.0	50	581	2.51	<0.28	6.7	9.2	28
350.2	shelly	---	---	817	3.87	<0.25	8.1	14.0	25
353.4	sandy	7.1	39	1290	5.44	<0.36	14.0	21.0	50
358.2	shelly	---	---	474	3.57	<0.17	5.7	14.0	21
362.4	sandy	7.3	15	1744	3.15	<0.41	15.0	28.0	50
368.0	sandy	7.1	86	773	2.39	<0.22	4.6	6.5	13
374.0	sandy	7.3	98	914	1.17	<0.26	7.2	11.0	22
379.9	sandy	7.1	39	198	2.16	<0.19	3.6	3.8	5
388.0	clayey	7.5	179	258	1.97	<0.25	6.4	12.0	24
392.4	clayey	7.4	71	457	1.98	<0.18	7.0	10.0	16
398.4	clayey	---	---	261	4.37	<0.27	8.2	16.0	13
399.9	sandy	7.7	132	439	2.14	<0.23	7.7	12.0	50
400.8	clayey	---	---	----	----	---	---	---	---
402.0	clayey	7.4	129	473	3.60	0.47	11.0	16.0	56
404.4	clayey	7.0	158	546	6.02	<0.29	11.0	19.0	76

Table C-4. (continued)

GIWW Mileage Statute Miles	Sediment Classification	pH	Eh	BOD_5 (ppm)	% Vol. Solids	Cd (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
405.0	sandy	7.7	283	339	3.57	<0.20	5.9	9.5	32
406.0	clayey	7.4	87	441	1.51	<0.24	7.1	10.0	21
411.5	clayey	7.1	123	974	2.86	<0.19	7.9	13.0	37
417.8	clayey	7.8	206	194	1.80	<0.34	67.0	12.0	47
421.5	clayey	7.2	71	382	3.47	0.62	10.0	4.0	29
428.4	clayey	7.2	85	1410	3.96	<0.28	31.0	15.0	34
434.8	clayey	7.1	-36	504	3.76	<0.27	8.3	15.0	25
437.3	clayey	7.0	130	765	5.13	0.64	15.0	17.0	32
440.7	sandy	7.0	123	575	3.61	0.75	9.3	15.0	22
441.5	sandy	---	---	358	1.81	1.5	6.0	11.0	17
442.5	sandy	7.2	135	787	2.65	0.79	8.2	15.0	25
447.0	sandy	7.5	105	978	2.76	0.88	21.0	15.0	32
453.5	sandy	7.2	76	172	1.93	0.64	8.1	13.0	24
460.5	sandy	7.4	83	704	4.65	1.0	9.8	18.0	33
466.2	sandy	7.6	88	667	5.30	<0.35	9.1	14.0	25
471.2	sandy	8.0	25	385	1.78	<0.25	7.1	9.8	25

Table C-4. (continued)

GIWW Mileage Statute Miles	Sediment Classification	pH	Eh	BOD_5 (ppm)	% Vol. Solids	Cd (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
479.0	sandy	7.5	401	----	----	----	----	---	---
485.2	sandy	7.3	94	95	0.44	<0.22	2.2	2.2	4
492.0	sandy	7.1	108	511	2.09	<0.21	3.9	7.6	12
498.4	clayey	7.4	158	1158	4.28	<0.37	8.1	21.0	31
505.2	sandy	7.5	218	172	1.11	<0.19	1.9	3.2	5
510.2	sandy	8.0	38	326	0.25	0.65	7.1	1.5	2
517.5	sandy	7.0	84	2120	7.77	<0.43	9.0	18.0	30
524.2	shelly	---	---	1791	8.02	0.80	9.6	27.0	33
530.1	sandy	7.4	346	347	2.14	0.59	3.7	12.0	9
536.3	silty	7.1	113	1020	6.32	<0.32	11.0	13.0	42
542.0	silty	7.1	140	1096	3.02	0.50	7.0	16.0	40
548.8	sandy	7.4	151	235	1.03	<0.23	3.7	7.0	15
555.6	silty	7.0	222	546	1.02	<0.17	2.3	3.4	6
561.8	sandy	7.2	44	970	2.39	<0.29	4.7	7.9	19
568.2	sandy	6.9	2	958	3.47	<0.38	4.0	12.0	12
574.6	silty	6.5	47	4360	12.03	<0.54	17.0	22.0	41

Table C-4. (continued)

GIWW Mileage Statute Miles	Sediment Classification	pH	Eh	BOD_5 (ppm)	% Vol. Solids	Cd (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)
580.8	silty	7.2	-210	2200	6.35	<0.44	11.0	19.0	34
587.0	sandy	6.8	-152	2668	11.35	<0.46	13.0	17.0	39
593.0	sandy	7.6	15	1598	5.09	<0.21	21.0	6.4	10
598.9	sandy	7.7	31	382	0.91	<0.20	2.0	2.6	4
605.0	sandy	7.4	12	56	0.78	<0.26	48.0	1.7	13
612.9	sandy	7.3	50	1073	7.67	<0.44	11.0	15.0	30
619.1	silty	6.8	-23	1359	7.73	<0.44	11.0	16.0	33
625.0	silty	6.7	166	1217	5.95	<0.43	11.0	23.0	34
631.4	silty	6.7	144	1667	8.69	0.97	71.0	17.0	49
638.3	clayey	6.6	126	164	2.68	0.69	6.5	13.0	22
644.1	sandy	7.2	211	151	2.86	0.34	19.0	12.0	32
650.8	sandy	6.9	-132	553	6.12	0.60	14.0	19.0	42
656.9	clayey	7.5	407	826	6.50	0.55	9.3	16.0	30
663.1	clayey	6.8	-164	618	4.35	0.59	6.5	14.0	28
668.4	clayey	7.8	301	243	4.52	0.56	30.0	17.0	58
675.2	clayey	7.2	162	497	2.25	0.94	12.0	16.0	31
682.1	clayey	7.0	146	592	3.65	0.59	10.0	17.0	35

Table C-5. Surface Physical Water Quality, May 1975

GIWW Mileage Statute Miles	Salinity (ppt)	Dissolved Oxygen (mg/l)	Dissolved Oxygen (% Sat.)	Temp. (°C)	pH	T.S. Solids (mg/l)	V.S. Solids (mg/l)
265.4	1.0	5.1	61.5	24	7.2	29	80
274.2	<1.0	5.7	69.2	25	7.1	39	110
278.0	<1.0	5.5	66.8	25	7.4	52	100
290.0	3.0	4.9	61.6	26	7.4	39	90
345.2	8.0	7.1	88.8	24	-	29	70
350.2	10.0	7.4	98.6	27	8.2	32	150
353.4	16.5	7.0	96.8	27	-	56	120
358.2	16.5	6.5	90.7	28	8.4	96	111
393.0	17.0	5.7	69.8	20	-	82	170
398.4	6.0	5.8	69.8	23	-	122	150
399.9	3.0	5.6	70.1	25	8.0	104	140
400.8	2.5	5.5	62.9	21	-	628	368
402.0	1.5	5.6	66.3	23	7.9	370	300

Table C-5. (continued)

GIWW Mileage Statute Miles	Salinity (ppt)	Dissolved Oxygen (mg/l)	Dissolved Oxygen (% Sat.)	Temp. (°C)	pH	T.S. Solids (mg/l)	V.S. Solids (mg/l)
404.4	3.5	6.3	80.7	27	7.9	64	170
619.1	32.0	6.3	T 93.4 B 93.4	28	-	-	-
631.4	29.0	7.4	112.3	29	8.6	-	-
635.1	29.0	7.0	108.6	30	8.4	-	-
638.3	29.0	7.8	121.0	30	8.7	-	-
640.7	30.0	7.4	T 115.0 B 108.8	30	8.6	-	-
644.1	27.0	7.4	113.5	30	8.3	99	240
647.7	32.0	6.3	T 97.0 B 95.5	29	8.2	58	150
650.8	32.0	5.8	T 89.6 B 89.6	29	-	-	150
653.8	29.0	6.0	91.0	29	-	96	130
656.9	29.0	6.0	91.0	29	-	105	70

Table C-5. (continued)

GIWW Mileage Statute Miles	Salinity (ppt)	Dissolved Oxygen (mg/l)	Dissolved Oxygen (% Sat.)	Temp. (°C)	pH	T.S. Solids (mg/l)	V.S. Solids (mg/l)
659.9	30.0	5.9	88.6	28	-	146	190
AC10[a]	12.0	8.3	114.9	29	8.3	33	140
AC34[b]	10.0	10.0	136.9	29	8.6	80	210

a AC10 - buoy number 10 approximately 1¼ mi up Arroyo Colorado from GIWW

b AC34 - buoy number 34 approximately 7¼ mi up Arroyo Colorado from GIWW

Table C-6. Surface Chemical Water Quality, May 1975

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	Cd (ppb)	Cu (ppb)	Pb (ppb)	Zn (ppb)
265.4	0.028	< 0.02	0.15	< 0.05	1.3	48	< 1	45
274.2	0.041	0.61	0.14	< 0.05	< 1.0	< 1	3	13
278.0	0.022	0.04	0.16	< 0.05	1.2	5	< 1	15
290.0	0.225	0.26	0.31	< 0.05	1.5	9	< 1	33
346.2	0.161	< 0.02	< 0.05	< 0.05	-	-	-	-
350.2	0.180	< 0.02	< 0.05	< 0.05	< 1.0	35	< 1	7
353.4	0.100	< 0.02	< 0.05	< 0.05	< 1.0	< 1	< 1	45
358.2	0.130	< 0.02	< 0.05	< 0.05	< 1.0	2	4	18
393.0	0.071	0.07	0.18	< 0.05	-	-	-	-
398.4	0.096	0.06	0.75	< 0.05	-	-	-	-
399.9	0.029	0.04	0.97	< 0.05	< 1.0	< 1	< 1	10
400.8	0.027	0.03	1.00	< 0.05	-	-	-	-
402.0	0.029	< 0.02	1.00	< 0.05	< 1.0	27	< 1	35
404.4	0.058	0.04	0.83	< 0.05	4.0	50	4	-

Table C-6. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	Cd (ppb)	Cu (ppb)	Pb (ppb)	Zn (ppb)
619.1	-	-	-	-	3.0	36	< 1	-
631.4	-	-	-	-	1.3	2	< 1	15
635.1	-	-	-	-	1.5	18	< 1	23
638.3	-	-	-	-	4.0	35	< 1	5
640.7	-	-	-	-	3.0	< 1	< 1	13
644.1	0.040	< 0.02	< 0.05	< 0.05	5.0	32	< 1	23
647.7	0.042	< 0.02	0.06	< 0.05	1.3	38	2	15
650.8	-	-	-	-	-	-	-	-
653.8	0.020	< 0.02	< 0.05	< 0.05	-	-	-	-
656.9	0.032	< 0.02	< 0.05	< 0.05	-	-	-	-
659.9	0.026	< 0.02	< 0.05	< 0.05	-	-	-	-
AC10[a]	0.105	< 0.02	0.51	0.08	9.0	2	< 1	21
AC34[b]	0.100	< 0.02	0.69	0.08	12.0	17	1	32

a AC10 - buoy number 10 approximately 1¼ mi. up Arroyo Colorado from GIWW

b AC34 - bouy number 34 approximately 7¼ mi. up Arroyo Colorado from GIWW

Table C-7. Sediment Quality, May 1975

GIWW Mileage Statute Miles	Cd (ppm)	Cu (ppm)	Pb (ppm)	Zn (ppm)	BOD_5 (ppm)	% Vol Solids
265.4	2.16	32.9	5.3	93	1856	5.48
274.2	0.63	7.4	15.4	22	652	2.55
278.0	0.97	17.9	47.3	71	2151	6.27
290.0	0.68	14.9	39.8	56	886	5.35
353.4	1.83	9.3	20.9	39	496	3.10
358.2	2.70	19.7	34.1	33	728	2.39
399.9	0.77	13.0	26.4	101	602	5.03
402.0	0.89	11.2	54.3	318	217	3.39
404.4	0.93	10.9	45.3	58	420	5.41
619.1	2.58	17.5	50.6	174	3597	9.92
631.4	1.36	11.0	45.6	34	1239	9.47
635.1	2.35	11.9	34.6	35	2000	9.43
638.3	0.93	12.5	18.2	27	1262	5.81

Table C-8. Physical Water Quality, August 1975

GIWW Mileage Statute Miles	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp. (°C)		Turbidity (FTU)	pH	
	T	B	T	B	T	B	T	B		T	B
265.4	0.3	-	6.4	5.8	85.1	-	30.0	-	29	6.5	-
274.2	0.8	1.1	6.4	6.2	85.1	82.6	30.0	30.0	24	7.0	6.9
Nec.2[a]	1.4	3.9	4.0	4.3	53.3	58.6	30.0	30.6	21	7.6	7.0
278.0	3.8	5.7	5.4	5.0	74.3	68.8	31.1	30.6	17	7.2	7.3
285.0	6.1	10.0	5.7	4.5	79.7	62.7	31.7	31.1	13	6.9	7.6
290.0	1.0	6.5	3.6	4.3	49.8	59.7	32.2	31.1	25	7.0	7.3
296.6	2.4	2.6	5.5	5.0	76.3	69.0	32.2	31.7	32	7.3	7.2
301.2	1.4	1.9	6.2	5.0	85.7	68.6	32.2	31.7	45	7.4	7.1
305.4	0.8	1.4	6.3	5.0	87.4	68.3	32.8	31.9	54	7.4	7.2
309.4	1.0	1.3	5.8	5.2	80.8	71.8	32.8	32.2	67	7.3	7.0
315.0	1.0	1.1	5.1	4.9	70.5	67.7	32.2	32.2	79	7.1	7.0
319.0	1.1	1.2	5.0	4.4	69.1	60.0	32.2	31.7	81	7.2	7.0
320.5	1.1	1.3	5.0	4.1	69.1	56.7	32.2	32.2	88	7.2	7.0

Table C-8. (continued)

GIWW Mileage Statute Miles	Salinity (ppt)		Dissolved Oxygen (mg/l(		(% Saturation)		Temp. (°C)		Turbidity (FTU)	pH	
	T	B	T	B	T	B	T	B		T	B
326.5	4.5	6.6	7.0	5.1	99.1	71.9	32.8	31.7	55	7.6	7.4
329.8	6.3	10.8	10.2	7.0	147.4	98.9	33.3	30.6	26	8.5	8.1
332.3	10.7	11.9	11.0	7.6	165.8	110.8	33.9	[illegible]	20	8.4	8.2
337.7	10.9	10.4	8.0	7.4	115.6	106.1	32.4	31.7	25	8.1	8.0
342.5	12.0	13.1	9.5	7.8	139.0	113.0	32.2	31.7	11	8.3	8.3
346.2	16.7	19.1	10.1	8.1	151.6	121.6	32.2	31.7	9	8.4	8.4
350.2	20.8	22.5	10.0	9.5	153.4	145.7	32.2	31.7	4	8.4	8.4
353.4	22.8	23.2	8.8	7.3	135.0	104.4	31.7	31.1	9	8.4	8.4
358.2	21.6	21.6	9.1	6.6	137.8	99.9	31.7	31.7	16	8.4	8.4
362.4	23.0	21.3	7.4	7.4	110.4	112.0	30.0	31.7	21	8.4	8.4
368.0	21.4	20.8	8.4	7.0	129.2	106.4	32.2	31.7	13	8.3	8.4
374.0	21.0	22.5	8.6	6.7	132.2	101.4	31.7	31.1	18	8.3	8.3
379.9	20.3	20.8	9.0	7.2	138.4	109.0	32.8	32.2	22	8.2	8.2

Table C-8. (continued)

GIWW Mileage Statute Miles	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp. (^{o}C)		Turbidity (FTU)	pH	
	T	B	T	B	T	B	T	B		T	B
388.0	29.3	28.8	8.4	7.0	133.3	110.1	31.7	31.1	14	8.3	8.3
392.4	28.7	28.0	8.6	6.8	135.8	107.1	31.7	31.7	12	8.3	8.3
395.6	22.6	23.5	8.6	7.6	133.1	116.6	32.2	31.7	43	8.3	8.3
399.9	17.0	18.8	8.6	6.5	133.4	98.0	33.9	32.2	55	8.1	8.1
BR30U[b]	6.5	20.3	8.5	6.0	122.8	93.9	33.3	33.3	14	7.9	7.2
400.8	7.6	23.8	8.2	5.2	117.8	82.7	33.3	33.3	9	7.6	8.2
402.0	16.2	17.7	11.0	7.0	160.3	105.5	33.3	32.2	46	8.3	8.2
404.4	13.2	20.1	9.0	5.6	144.4	100.2	34.4	32.2	36	8.4	8.4
405.0	17.7	20.6	8.9	9.4	134.5	145.8	32.2	32.8	21	8.4	8.5
SE33U[c]	13.4	15.2	6.1	6.0	88.3	87.3	31.7	31.1	16	8.1	8.3
406.0	23.6	27.7	6.8	6.6	104.1	999.5	31.1	30.6	19	8.3	8.3
411.5	16.9	16.9	6.5	7.4	95.5	109.0	31.1	31.1	35	8.4	8.4
417.8	15.0	14.5	6.4	6.1	93.7	88.9	31.7	31.7	37	8.4	8.4

Table C-8. (continued)

GIWW Mileage Statute Miles	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp. (°C)		Turbidity (FTU)	pH	
	T	B	T	B	T	B	T	B		T	B
421.5	15.8	15.6	6.6	6.5	95.6	95.5	31.1	31.7	33	8.4	8.5
428.4	7.7	8.9	7.5	6.8	104.7	95.9	31.7	31.7	29	8.5	8.5
434.8	13.2	12.6	7.6	6.9	111.2	100.3	32.2	32.2	25	8.4	8.4
437.3	16.2	14.8	8.1	6.8	119.3	100.6	31.7	32.2	28	8.4	8.4
440.7	17.7	17.1	7.1	6.4	107.5	96.3	32.2	32.2	12	8.3	8.4
441.5	6.1	16.6	7.2	6.2	102.2	93.1	32.2	32.2	18	8.1	8.3
442.5	15.4	15.4	7.3	6.5	108.4	96.5	32.2	32.2	15	8.2	8.4
447.0	12.6	11.9	8.5	7.3	124.6	107.1	32.2	32.8	26	8.4	8.4
453.5	16.0	17.4	9.3	7.7	138.1	113.9	32.2	31.7	24	8.4	8.4
460.4	22.0	22.2	7.9	3.3	122.5	50.1	32.2	31.7	14	8.4	8.1
466.2	23.5	25.4	8.2	5.6	126.4	87.5	31.7	31.7	6	8.4	8.3
471.2	27.0	28.7	8.6	8.6	137.1	136.4	32.2	31.7	5	8.4	8.5
479.0	14.3	18.0	8.8	7.2	129.9	106.9	32.2	31.7	12	8.5	8.5

Table C-8. (continued)

GIWW Mileage Statute Miles	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp. (°C)		Turbidity (FTU)	pH	
	T	B	T	B	T	B	T	B		T	B
485.2	7.6	8.7	8.6	7.3	122.5	105.1	32.2	32.2	20	8.6	8.6
492.0	4.0	4.6	8.1	7.5	113.1	104.6	31.7	31.1	35	8.6	8.6
498.4	8.7	12.7	9.5	7.6	135.3	109.4	32.2	31.7	50	8.5	8.4
505.2	18.9	18.5	8.6	8.0	129.7	119.1	32.2	31.7	18	8.4	8.5
510.0	19.5	19.1	9.0	8.0	136.6	113.8	32.2	31.7	16	8.4	8.5
517.5	17.9	20.3	8.4	6.6	124.2	98.9	31.7	31.7	9	8.4	8.5
530.1	27.3	27.3	7.1	6.2	111.4	97.3	31.7	31.7	8	8.5	8.8
536.3	26.1	28.0	9.0	7.3	142.8	115.5	32.8	31.7	10	8.6	8.6
542.0	25.1	26.7	10.5	9.0	165.4	140.9	32.2	31.7	6	8.4	8.5
548.8	27.3	27.3	9.4	8.6	147.4	134.9	31.7	31.7	4	8.5	8.6
555.6	32.9	32.9	4.7	5.2	74.4	82.3	30.0	30.0	5	8.5	8.6
561.8	34.8	-	6.0	5.6	92.2	-	31.1	30.0	4	8.6	8.7
568.2	34.3	34.3	6.6	6.7	106.6	108.3	31.1	31.1	7	8.5	8.6

Table C-8. (continued)

GIWW Mileage Statute Miles	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp. (°C)		Turbidity (FTU)	pH	
	T	B	T	B	T	B	T	B		T	B
574.6	33.5	32.2	6.5	6.2	104.8	99.9	31.1	31.1	8	8.5	8.6
580.8	32.5	32.5	6.3	6.4	100.6	102.2	30.6	0.6	11	8.5	8.6
587.0	28.9	28.7	6.9	7.6	109.2	120.3	31.1	31.7	8	8.6	8.6
593.0	29.5	28.0	7.4	6.9	117.3	109.0	31.1	31.7	5	8.6	8.6
599.9	29.5	28.0	6.9	7.2	109.5	113.7	31.1	31.7	6	8.7	8.7
605.0	29.5	27.6	7.8	7.2	123.7	115.0	31.1	32.2	8	8.6	8.6
612.9	28.9	28.2	6.3	6.3	99.7	99.5	31.1	31.1	5	8.6	8.7
619.1	27.0	27.5	8.2	6.6	129.8	102.8	32.2	31.1	12	8.5	8.6
625.0	26.1	25.6	8.4	6.0	132.7	94.8	32.2	32.2	7	8.5	8.4
631.1	27.6	28.2	9.2	7.5	146.3	121.7	32.2	32.2	12	8.5	8.6
638.3	29.4	29.2	8.6	5.5	139.0	89.9	32.8	33.3	14	8.5	8.4
644.1	27.4	30.2	8.3	7.3	132.9	116.1	32.8	31.7	15	8.5	8.5
AC10[d]	14.1	31.5	10.3	5.8	152.6	92.2	32.8	31.1	11	8.6	8.5

Table C-8. (continued)

GIWW Mileage Statute Miles	Salinity (ppt)		Dissolved Oxygen (mg/l)		Dissolved Oxygen (% Saturation)		Temp. (°C)		Turbidity (FTU)	pH	
	T	B	T	B	T	B	T	B		T	B
AC34[e]	11.9	30.5	15.0	2.6	220.4	41.6	32.8	31.7	9	8.5	8.4
650.8	33.9	33.9	7.1	5.9	115.3	95.8	31.7	31.7	10	8.5	8.6
656.9	33.3	32.8	8.1	7.8	134.0	128.1	32.8	32.2	13	8.5	8.6
663.1	31.8	32.6	9.4	8.8	146.5	137.4	29.4	29.4	6	8.4	8.5
668.9	31.6	31.9	8.8	8.5	136.8	132.4	29.4	29.4	7	8.4	8.4
675.2	28.9	29.5	8.6	7.1	132.8	103.7	30.0	29.4	6	8.2	8.2
682.1	28.9	29.5	9.6	8.0	148.3	124.4	30.0	30.0	5	8.2	8.4

a Nec.2 - samples obtained in the Neches River 1½ mile upstream from GIWW

b BR30U - samples obtained in the Brazos River ½ mile upstream from GIWW

c SB33U - samples obtained in the San Bernard 6 miles upstream from GIWW

d AC10 - buoy number 10 in Arroyo Colorado approximately 1¼ miles upstream from GIWW

e AC34 - buoy number 34 in Arroyo Colorado approximately 7¼ miles upstream from GIWW

Table C-9. Chemical Water Quality, August 1975

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)
265.4	0.025	0.75	0.05	<.05	14	4	-
274.2	0.032	0.68	0.10	<.05	13	2	10
Nec.2[a]	<0.025	0.48	0.08	<.05	17	3	10
278.0	0.032	0.35	0.10	<.05	20	3	9
285.0	0.039	0.36	0.14	<.05	12	3	9
290.0	0.097	0.70	0.05	<.05	32	6	10
296.6	0.163	0.92	0.10	<.05	52	10	13
301.2	0.146	0.62	0.19	.06	78	50	16
305.4	0.133	0.37	0.25	.11	114	14	15
309.4	0.132	0.12	0.58	.18	160	15	14
315.0	0.097	0.13	0.56	.15	173	17	10
319.0	0.097	0.13	0.45	.10	147	17	10
320.5	0.069	0.18	0.56	.10	83	4	12
326.5	0.057	0.18	0.25	<.05	79	7	10

Table C-9. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)
329.8	0.057	0.15	0.08	<.05	27	1	18
332.3	0.072	0.04	<0.05	<.05	38	2	8
337.7	0.107	0.16	<0.05	<.05	42	5	8
342.5	0.266	0.04	<0.05	<.05	25	6	8
346.2	0.183	0.05	<0.05	<.05	33	9	4
350.2	0.171	0.02	<0.05	<.05	45	10	3
353.4	0.167	0.25	<0.05	<.05	49	10	3
358.2	0.170	0.04	<0.05	<.05	39	7	5
362.4	0.117	0.27	<0.05	<.05	49	9	5
368.0	0.160	0.24	<0.05	<.05	48	9	4
374.0	0.105	0.24	<0.05	<.05	57	14	4
379.9	0.113	0.18	<0.05	<.05	46	10	5
388.0	0.062	0.17	<0.05	<.05	40	11	1
392.4	0.067	0.17	<0.05	<.05	50	14	-

Table C-9. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)
395.6	0.083	0.35	0.15	<.05	94	19	-
399.9	0.065	0.56	0.23	<.05	77	15	3
BR30U[b]	0.046	0.22	0.30	<.05	35	11	4
400.8	0.052	0.60	0.35	<.05	29	17	3
402.0	0.064	0.14	0.13	<.05	85	15	4
404.4	0.051	0.05	<0.05	<.05	56	8	5
405.0	0.093	0.04	<0.05	<.05	52	12	-
SB33U[c]	0.110	0.04	<0.05	<.05	33	5	6
406.0	0.094	0.17	<0.05	<.05	51	13	4
411.5	0.089	0.04	<0.05	<.05	53	11	7
417.8	0.093	0.09	<0.05	<.05	54	11	6
421.5	0.073	0.06	<0.05	<.05	46	12	5
428.4	0.058	0.04	<0.05	<.05	38	9	7
434.8	<0.025	0.05	<0.05	<.05	36	11	23

Table C-9. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)
437.3	0.041	0.04	<0.05	<.05	47	15	4
440.7	0.041	0.04	<0.05	<.05	33	13	3
441.5	0.034	0.12	<0.05	<.05	38	13	4
442.5	0.049	0.04	<0.05	<.05	30	10	3
447.0	0.043	0.04	<0.05	<.05	39	12	5
453.5	0.059	0.04	<0.05	<.05	45	13	4
460.4	0.050	0.03	<0.05	<.05	45	15	4
466.2	0.025	0.10	<0.05	<.05	37	15	3
471.2	0.046	0.11	<0.05	<.05	52	19	2
479.0	0.055	0.05	<0.05	<.05	46	16	3
485.2	0.062	0.07	<0.05	<.05	36	12	5
492.0	0.041	0.15	<0.05	<.05	43	11	4
498.4	0.082	0.11	<0.05	<.05	80	16	5
505.2	0.056	0.03	<0.05	<.05	50	16	4

Table C-9. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)
510.0	0.056	0.06	< 0.05	< .05	37	14	4
517.5	0.059	0.04	< 0.05	< .05	42	18	5
530.1	0.030	0.18	< 0.05	< .05	57	22	4
536.3	0.037	0.17	< 0.05	< .05	54	23	4
542.0	0.076	0.18	< 0.05	< .05	59	25	1
548.8	0.058	0.19	0.06	< .05	55	23	4
555.6	0.025	0.20	< 0.05	< .05	62	24	3
561.8	0.030	0.14	< 0.05	< .05	72	28	6
568.2	0.103	0.18	0.06	< .05	70	25	7
574.6	0.055	0.20	< 0.05	< .05	73	28	9
580.8	0.057	0.17	< 0.05	< .05	62	22	10
587.0	0.067	0.14	< 0.05	< .05	76	18	10
593.0	0.072	0.17	< 0.05	< .05	63	19	10
599.9	0.058	0.08	0.06	< .05	61	17	11

Table C-9. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)
605.0	0.068	0.06	<0.05	<.05	79	23	10
612.9	0.073	0.17	<0.05	<.05	68	20	9
619.1	0.082	0.08	<0.05	<.05	65	20	9
625.0	0.095	0.14	<0.05	<.05	66	21	1
631.4	0.048	0.30	<0.05	<.05	67	22	9
638.3	0.079	0.06	<0.05	<.05	72	21	8
644.1	0.077	0.05	<0.05	<.05	65	25	10
AC10[d]	0.100	0.40	<0.05	<.05	64	21	9
AC34[e]	0.110	0.21	<0.05	<.05	33	15	7
650.8	0.041	0.03	<0.05	<.05	82	27	9
656.9	0.039	0.02	<0.05	<.05	80	27	6
663.1	0.050	0.03	<0.05	<.05	73	25	9
668.9	0.039	0.06	<0.05	<.05	67	25	6

Table C-9. (continued)

GIWW Mileage Statute Miles	PO_4-P (mg/l)	NH_3-N (mg/l)	NO_3-N (mg/l)	NO_2-N (mg/l)	T.S. Solids (mg/l)	V.S. Solids (mg/l)	TOC (mg/l)
675.2	0.075	0.09	< 0.05	< .05	52	21	5
682.1	0.050	0.09	< 0.05	< .05	48	13	1

a Nec.2 - samples obtained in the Neches River 1½ mile upstream from GIWW

b BR30U - samples obtained in the Brazos River ½ mile upstream from GIWW

c SB33U - samples obtained in the San Bernard 6 miles upstream from GIWW

d AC10 - buoy number 10 in Arroyo Colorado approximately 1¼ miles upstream from GIWW

e AC34 - buoy number 34 in Arroyo Colorado approximately 7¼ miles upstream from GIWW

Table C-10. Metals in Water, August 1975

GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)	GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)
265.4	<1.0	<1.0	<4.0	332.3	<1.0	<1.0	<4.0
274.2	<1.0	<1.0	<4.0	337.7	<1.0	<1.0	<4.0
Mec.2[a]	<1.0	<1.0	<4.0	342.5	<1.0	<1.0	<4.0
278.0	<1.0	<1.0	<4.0	346.2	<1.0	<1.0	<4.0
285.0	<1.0	<1.0	<4.0	350.2	<1.0	<1.0	<4.0
290.0	<1.0	<1.0	<4.0	353.4	<1.0	<1.0	<4.0
296.6	<1.0	<1.0	<4.0	358.2	<1.0	<1.0	<4.0
301.2	<1.0	<1.0	<4.0	362.4	<1.0	<1.0	<4.0
305.4	<1.0	19.1	<4.0	368.0	<1.0	<1.0	<4.0
309.4	<1.0	<1.0	<4.0	374.0	<1.0	<1.0	<4.0
315.0	<1.0	<1.0	<4.0	379.9	<1.0	<1.0	<4.0
319.0	<1.0	7.7	<4.0	388.0	<1.0	<1.0	<4.0
320.5	<1.0	<1.0	<4.0	392.4	<1.0	<1.0	<4.0
325.5	<1.0	<1.0	<4.0	395.6	<1.0	<1.0	<4.0
329.8	<1.0	<1.0	<4.0	399.9	<1.0	<1.0	<4.0

Table C-10. (continued)

GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)	GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)
SR30U[b]	<1.0	<1.0	<4.0	442.5	<1.0	<1.0	<4.0
400.8	<1.0	6.3	<4.0	447.0	<1.0	<1.0	<4.0
402.0	<1.0	<1.0	<4.0	453.5	<1.0	<1.0	<4.0
404.4	<1.0	<1.0	<4.0	460.4	<1.0	<1.0	<4.0
405.0	<1.0	<1.0	<4.0	466.2	<1.0	<1.0	<4.0
SB33U[c]	<1.0	<1.0	<4.0	471.2	5.5	<1.0	<4.0
406.0	<1.0	<1.0	<4.0	479.0	<1.0	<1.0	<4.0
411.5	<1.0	<1.0	<4.0	485.2	<1.0	<1.0	<4.0
417.8	<1.0	<1.0	<4.0	492.0	1.4	<1.0	<4.0
421.5	<1.0	<1.0	<4.0	498.4	<1.0	<1.0	<4.0
428.4	<1.0	<1.0	<4.0	505.2	<1.0	<1.0	<4.0
434.8	<1.0	<1.0	<4.0	510.0	<1.0	<1.0	<4.0
437.3	<1.0	<1.0	<4.0	517.5	<1.0	<1.0	<4.0
440.7	<1.0	<1.0	<4.0	530.1	<1.0	<1.0	<4.0
441.5	<1.0	<1.0	<4.0	536.3	1.2	<1.0	<4.0

Table C-10. (continued)

GIWW Mileage Statute Miles	Cd (ppb)	Cu (ppb)	Pb (ppb)
542.0	1.2	<1.0	<4.0
548.8	<1.0	<1.0	<4.0
555.6	<1.0	<1.0	<4.0
561.8	<1.0	<1.0	<4.0
568.2	1.6	<1.0	<4.0
574.6	1.6	<1.0	<4.0
580.8	<1.0	<1.0	<4.0
587.0	<1.0	1.0	<4.0
593.0	<1.0	<1.0	<4.0
599.9	<1.0	<1.0	<4.C
605.0	<1.0	<1.0	<4.0
612.9	<1.0	<1.0	<4.0
619.1	<1.0	<1.0	<4.0
625.0	<1.0	<1.0	<4.0
631.4	<1.0	<1.0	<4.0
638.3	<1.0	<1.0	<4.0
644.1	<1.0	<1.0	<4.0
AC10[d]	<1.0	<1.0	<4.0
AC34[e]	<1.0	<1.0	<4.0
650.8	<1.0	<1.0	<4.0
656.9	<1.0	<1.0	<4.0
663.1	<1.0	<1.0	<4.0
668.9	<1.0	<1.0	<4.0
675.2	<1.0	1.9	<4.0
682.1	<1.0	<1.0	<4.0

Table C-10. (continued)

a Nec.2 - samples obtained in the Neches River 1½ mile upstream from GIWW

b BR30U - samples obtained in the Brazos River ½ mile upstream from GIWW

c SB33U - samples obtained in the San Bernard 6 miles upstream from GIWW

d AC10 - buoy number 10 in Arroyo Colorado approximately 1¼ miles upstream from GIWW

e AC34 - buoy number 34 in Arroyo Colorado approximately 7¼ miles upstream frpm GIWW

TABLE C-11. Metals in Sediments, August 1975.

Station	GIWW Mileage Statute Miles	Cd ppm	Cu ppm	Hg ppm	Pb ppm	Se ppm	Zn ppm
29	399.9	< 3	16	---	---	8	155
31	402.0	< 3	16	---	---	16	97
32	404.4	< 3	14	---	---	17	115
33	405.0	< 3	3	---	---	8	36
34	406.0	< 3	8	---	19	6	27
42	441.5	---	---	0.2	---	---	---
43	442.5	---	---	0.2	---	---	---
44	447.0	---	---	0.1	---	---	---
45	453.5	---	---	0.3	---	---	---
46	460.4	---	---	0.1	---	---	---
47	466.2	---	---	0.4	---	---	---
48	471.2	---	---	0.2	---	---	---
49	479.0	---	---	0.2	---	---	---
50	485.2	---	---	0.7	---	---	---
73	631.4	< 3	4	---	21	---	16
74	638.3	< 3	8	---	22	---	28
75	644.1	< 3	5	---	18	---	16

APPENDIX D

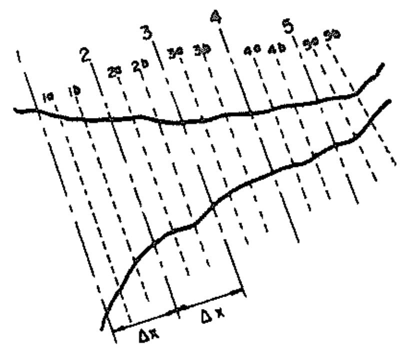
One-Dimensional Hydrodynamic Model

A one-dimensional hydrodynamic model developed by Harleman and Lee (1969) by using the finite difference scheme was used in this study. Harleman and Lee developed a computer program which can be applied in computing tides and tidal currents in estuaries and canals connecting two bodies of water. Minor modifications of the original computer program were made so that differences in the mean sea level at both ends of the canal can be accounted for. A brief description of the original program follows below; however, for more detailed information of the original program (including program listing), original publication should be consulted.

Schematization

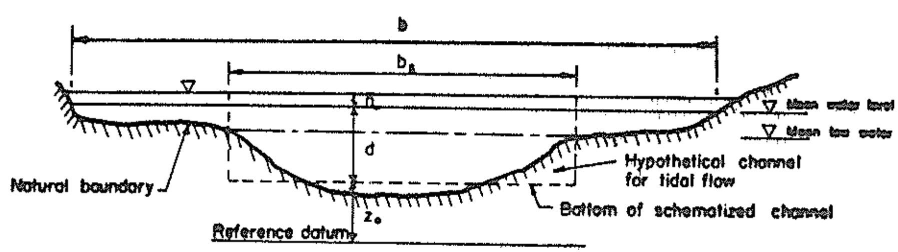
In a one-dimensional finite difference formulation it is necessary to divide the estuary or canal into a discrete number of longitudinal segments and to assign particular geometric characteristics to these segments. Since the number of segments which can be considered is limited, simplification and averaging are necessary. This process is called "schematization".

The longitudinal schematization of an estuary is shown in Figure D-1 where the longitudinal segment length is Δx. Figure D-2 shows the transverse schematization. The transverse geometry assigned to section 2 can be taken as the average of the transverse geometries of sections 1b, 2 and 2a, while that for section 3 would be the average of 2b, 3 and 3a, etc. The cross sections obtained as described above



(from Harleman and Lee, 1969)

Figure D-1. Longitudinal Schematization of an Estuary



(from Harleman and Lee, 1969)

Figure D-2. Transverse Schematization of an Estuary should be plotted with reference to an arbitrary horizontal reference datum.

Basic Equations and Finite Difference Formulation

The basic equations used in the non-linear, finite difference formulation are the one-dimensional continuity and momentum equations. They are

Continuity Equation

$$b \frac{\partial \eta}{\partial t} + \frac{\partial Q}{\partial x} - q = 0 \tag{1}$$

Momentum Equation

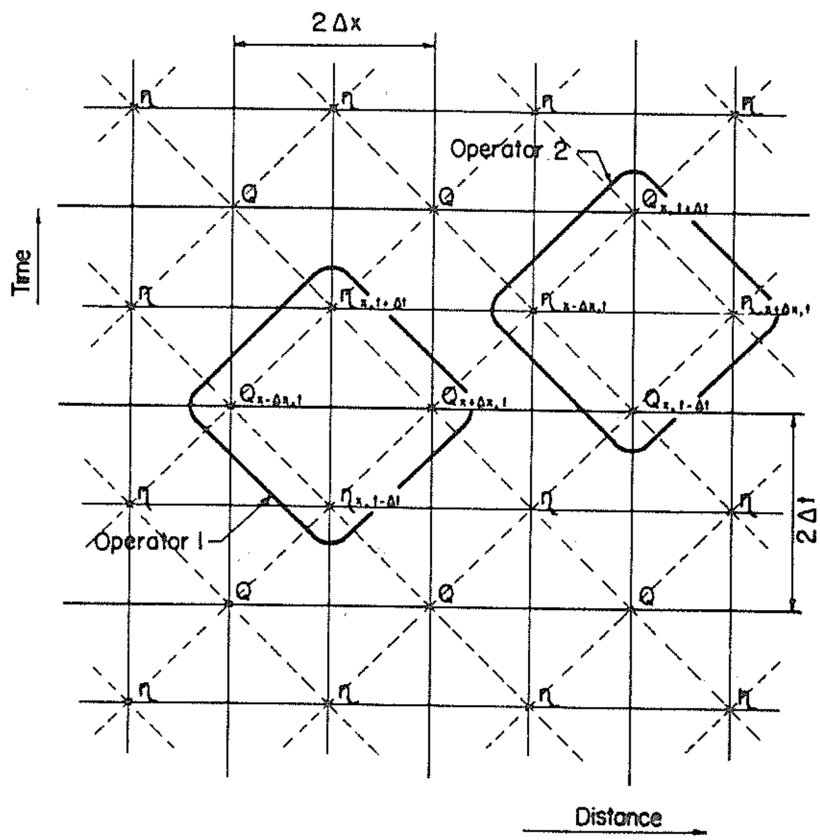
$$\frac{1}{A} \frac{\partial Q}{\partial t} + \frac{2Q}{A^2} q - \frac{2bQ}{A^2} \frac{\partial \eta}{\partial t} + g \left[\frac{\partial Z_o}{\partial x} + \frac{\partial d}{\partial x} + \frac{\partial \eta}{\partial x}\right] + g \frac{Q|Q|}{A^2 C^2 R} = 0 \tag{2}$$

Equations (1) and (2) constitute the pair of equations for the finite difference formulation in which the surface elevation η and the discharge Q are the unknowns. Explicit scheme employing a staggered arrangement commonly known as a diagonal mesh is used here in order to solve Equations (1) and (2).

The finite difference operators are shown in Figure D-3 in which the basic rectangular grid spacing is Δx and Δt.

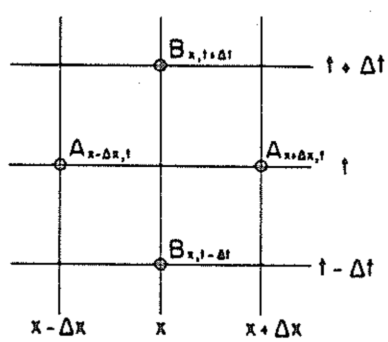
Two essential features of the operators should be noted:

1. Along any one line of the x, t grid, only one unknown dependent variable is defined (either η or Q).
2. The unknown variables η and Q are defined on alternate grid lines, both in time and distance, so that the basic space and



(from Harleman and Lee, 1969)

Figure D-3. Details of a Diagonal Mesh



(from Harleman and Lee, 1969)

Figure D-4. Definition Sketch for Central Differences Equations time intervals for a diagonal mesh relating either η or Q are $2\Delta x$ and $2\Delta t$, respectively.

The associated central finite difference equations, which define the first order partial derivatives with respect to space and time are shown in Figure D-4, as

$$\frac{\partial A}{\partial x} = \frac{A_{x+\Delta x,\ t} - A_{x-\Delta x,\ t}}{2\Delta x} \qquad (3)$$

$$\frac{\partial B}{\partial t} = \frac{B_{x,\ t+\Delta t} - B_{x,\ t-\Delta t}}{2\Delta t} \qquad (4)$$

where A and B are any unknown dependent variables. In the same manner, equations of continuity and momentum can be written in the finite difference form as shown in the following:

Continuity Equation

$$\frac{b_{x,t}\,[\eta_{x,\ t+\Delta t} - \eta_{x,\ t-\Delta t}]}{2\Delta t} + \frac{Q_{x+\Delta x,\ t} - Q_{x-\Delta x,\ t}}{2\Delta x}$$

$$- \frac{[Q_{trib}]_x}{2\Delta x} = 0 \qquad (5)$$

where $[Q_{trib}]_x$ = total inflow due to tributary streams entering the estuary or canal between $(x + \Delta x)$ and $(x - \Delta x) = q(2\Delta x)$.

Momentum Equation

$$\frac{1}{A_{x,t}}\left[\frac{Q_{x,\ t+\Delta t} - Q_{x,\ t-\Delta t}}{2\Delta t}\right] + \frac{2Q_{x,\ t-\Delta t}[Q_{trib}]_x}{[A_{x,t}]^2\ 2\Delta x}$$

$$- \frac{2b_{x,t}\ Q_{x,t-\Delta t}}{[A_{x,t}]^2} \cdot \frac{1}{2}\left[\frac{\eta_{x-\Delta x,\ t} - \eta_{x-\Delta x,\ t-2\Delta t}}{2\Delta t} + \frac{\eta_{x+\Delta x,\ t} - \eta_{x+\Delta x,\ t-2\Delta t}}{2\Delta t}\right]$$

$$+ \frac{g[Z_{o_{x+\Delta x}} - Z_{o_{x-\Delta x}}]}{2\Delta x} + \frac{g[d_{x+\Delta x} - d_{x-\Delta x}]}{2\Delta x} + \frac{g[\eta_{x+\Delta x,\ t} - \eta_{x-\Delta x,\ t}]}{2\Delta x}$$

$$+ \frac{g|Q_{x,\ t-\Delta t}|}{[C_{x,t}]^2[A_{x,t}]^2 R_{x,t}} \cdot \frac{1}{2}[Q_{x,\ t+\Delta t} + Q_{x,\ t-\Delta t}] - W_{x,t} = 0 \tag{6}$$

where:

$W_{x,t}$ = wind stress term defined by Equation (11) for a rectangular or schematized section

$$A_{x,t} = b_{sx}[d_x + \tfrac{1}{2}[\eta_{x+\Delta x,\ t} - \eta_{x-\Delta x,\ t}]] \tag{7}$$

$$b_{x,t} = b_x \tag{8}$$

$$R_{x,t} = \frac{A_{x,t}}{b_{s_x} + 2d_x + \eta_{x+\Delta x,\ t} + \eta_{x-\Delta x,\ t}} \tag{9}$$

The Chezy coefficient may be expressed in terms of the Manning roughness n_x (which may vary with x) and the hydraulic radius

$$C_{x,t} = \frac{1.49}{n_x}[R_{x,t}]^{1/6} \quad \text{[ft-sec units]} \tag{10}$$

A water surface wind stress term may be added to the momentum equation if it is desired to include the effect of local wind on the tidal motion. The wind term may be expressed as

$$W_{x,t} = \frac{\beta_W\ \rho_a|V_x \cos\psi_x|\ V_x \cos\psi_x}{\rho\ d_{x,t}} \tag{11}$$

where:

β_x = wind shear stress coefficient = 0.0026

ρ_a = density of air

ρ = density of water

V_x = absolute wind speed

ψ_x = angle between the direction of the wind and the longitudinal axis of the channel.

In Equations (5) and (6), the basic partial differential equations have been transformed into algebraic equations, each containing one unknown, $\eta_{x,\ t\ +\ \Delta t}$ in Equation (5), and $Q_{x,\ t\ +\ \Delta t}$ in Equation (6). The two equations can be solved by a computer in a straightforward manner. Referring to Figure D-3, assume that from previous computations all values of η and Q are known along the horizontal grid lines n + 1. Values of η along the grid line n +2 can be computed explicitly, one at a time, by applying Equation (5) shown by operator 1. Thereafter all values of Q along the grid line n + 3 can be determined by using Equation (6) shown by operator 2. Thus, by consecutive advancements in time steps of Δt each, the tidal elevations and discharges confined within the end boundaries of the tidal channel are computed alternately by repeating the procedure described above.

After the tidal elevations and discharges have been calculated at the grid points, the average velocity in the longitudinal direction can be calculated by

$$u = Q/A \tag{12}$$

Initial Conditions and Quasi-Steady State Solution

It is necessary to assume initial values of η and Q throughout the channel in order to begin the numerical calculations. Since as the solution proceeds forward in time, the property of the hyperbolic partial differential equation is such that the effect of the assumed initial condition diminishes rapidly, it may be assumed that $\eta = 0$ at $t = 0$ and $Q = 0$ at $t = \Delta t$ in the absence of any other information.

Using the known boundary conditions for one tidal cycle, the finite difference calculation proceeds to the end of the first tidal cycle $T + \Delta t$ (where T is the tidal period). The values of η at $t = T$ and Q at $t = T + \Delta t$ become the new initial conditions and the tidal cycle is repeated with the same boundary conditions. The repeated computation ends when the tidal elevations obtained in the $(k + 1)$th cycle differ from those obtained in the kth cycle by an amount not greater than an acceptable error. The solution obtained at the $(k + 1)$th tidal cycle is referred to as "quasi-steady state solution", and is independent of the assumed initial conditions.

Transient Solutions

If a continuous tidal record extending over more than one tidal period is available as an ocean boundary condition, a transient solution can be obtained by using the boundary condition of the first tidal cycle of the record to generate a quasi-steady state solution. Thereafter, the tidal conditions obtained at the end of the quasi-steady state solution can be utilized as the initial conditions for the remainder of the tidal record.

Numerical Stability Criteria

In order to obtain a stable solution in an explicit scheme, the following stability criterion can be used as a first approximation for the determination of Δx and Δt:

$$\Delta t < \frac{\Delta x}{\sqrt{g(d_e + \eta_e)}} \tag{13}$$

where:

d_e = depth of water below MSL at ocean end

η_e = amplitude of ocean tide

Since the magnitude of the friction term in the momentum equation has an influence on the stability, if an unstable solution results after Equation (13) has been satisfied it may be necessary to adjust Δx or Δt.

The space and time increments Δx and Δt should be chosen depending on the inequality of Equation (13) and the limitations imposed by computer storage capacity.

Required Input Data

The required input data for the execution of the computer program consist of:

(1) Geometric Data

(2) Boundary Conditions

η must be specified as a function of time, for at least one tidal cycle.

(3) Initial Conditions

η and Q can be set equal to zero initially.

(4) Resistance Coefficient

The Manning coefficient must be specified as a function of x. Past records of tidal elevation should be used to determine n by matching the computer solution to the field observations. In general the Manning coefficients are in the range of 0.020 to 0.040.

(5) Wind Data

Wind velocity and direction observations are required if it is desired to consider the effect of local winds on the tidal motion.

Output

The output from the computer solution consists of the tidal elevation η, the tidal discharge Q and the tidal velocity u at alternate grid points both in time and space. The discharge and velocity are determined for the same grid points.

Solutions for points of interest not falling on grid points can be obtained through numerical interpolations of the results obtained at the neighboring grid points, or by plotting the results in graphical form.